Fuel Characterization and Mapping

Fuels Products of the LANDFIRE Project

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***Abstract**—The LANDFIRE project is a collaborative interagency effort designed to provide seamless, nationally consistent, locally relevant geographic information systems (GIS) data layers depicting wildland fuels, vegetation and fire regime characteristics. The LANDFIRE project is the first of its kind and offers new opportunity for fire management and research activities. Here we introduce the LANDFIRE wildland fuels data layers including fire behavior fuel models, canopy bulk density, canopy base height, canopy cover, canopy height and new Fuel Loading Models. Specifically, we focus on the methods and data used to create these layers and present preliminary assessments. These key fuels layers will support fuels and smoke management and fire behavior modeling in addition to providing essential information for evaluating and managing wildland fires, seamlessly and consistently.*

Introduction

Wildland fuels are critical elements in wildland fire planning and management activities. Wildland fuels are needed to parameterize consumption models, for example First Order Fire Effects Model (FOFEM) and fire behavior models such as NEXUS (Scott 1999), BehavePlus (Andrews 2003) and FARSITE (Finney 1998). These models can be used for two basic but critically important purposes; prioritizing fuel treatments and assessing fire behavior and effects in wildland fire suppression activities. Data to drive these models are lacking for most federal lands. These issues led the Wildland Fire Leadership Council, a group of senior administration executives representing all land management agencies in the country, to charter the LANDFIRE Project. The LANDFIRE project is currently mapping or developing geospatial data to meet the need for continuous, consistent, unbiased and scientifically produced fuels layers. In particular, LANDFIRE produces the fuels layers needed to run FARSITE including fire behavior fuel models, both the Anderson (1982) models (13 fire behavior fuel models) and the relatively newer Scott and Burgan (2005) set, canopy cover, canopy height, canopy bulk density and canopy base height. For fire effects analysis, a new set of Fuel Loading Models is being developed that focus on providing the necessary inputs to run FOFEM spatially. This paper explains methods and tools employed by LANDFIRE to map each of these fuel products.

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Methods

Upstream Products

The fuels layers rely on previously produced LANDFIRE layers and ancillary data (fig. 1) including existing vegetation type (EVT), canopy cover (CC), canopy height (CH), environmental site potential (ESP), Enhanced Thematic Mapper (ETM) imagery, digital elevation model (DEM) and associated derivatives and biophysical gradients. A brief explanation of these data is required so that the fuels mapping process can be discussed and understood with clarity.

Reference Database—The LANDFIRE reference database forms the foundation for nearly all LANDFIRE deliverables. It is used for developing training sites for imagery classification; validating and testing simulation models; developing vegetation classifications; creating empirical models; determining and archiving data layer attributes and; assessing the accuracy of maps and models (Caratti 2006). The reference database stores all relevant plot level information and provides the means to generate, test, and validate predictive models and LANDFIRE deliverables. Data have been received from a variety of sources in various forms, though the United States Forest Service has been the largest contributor with approximately 56,000 plots (~40% of the total). Roughly 140,000 plots have been archived in the

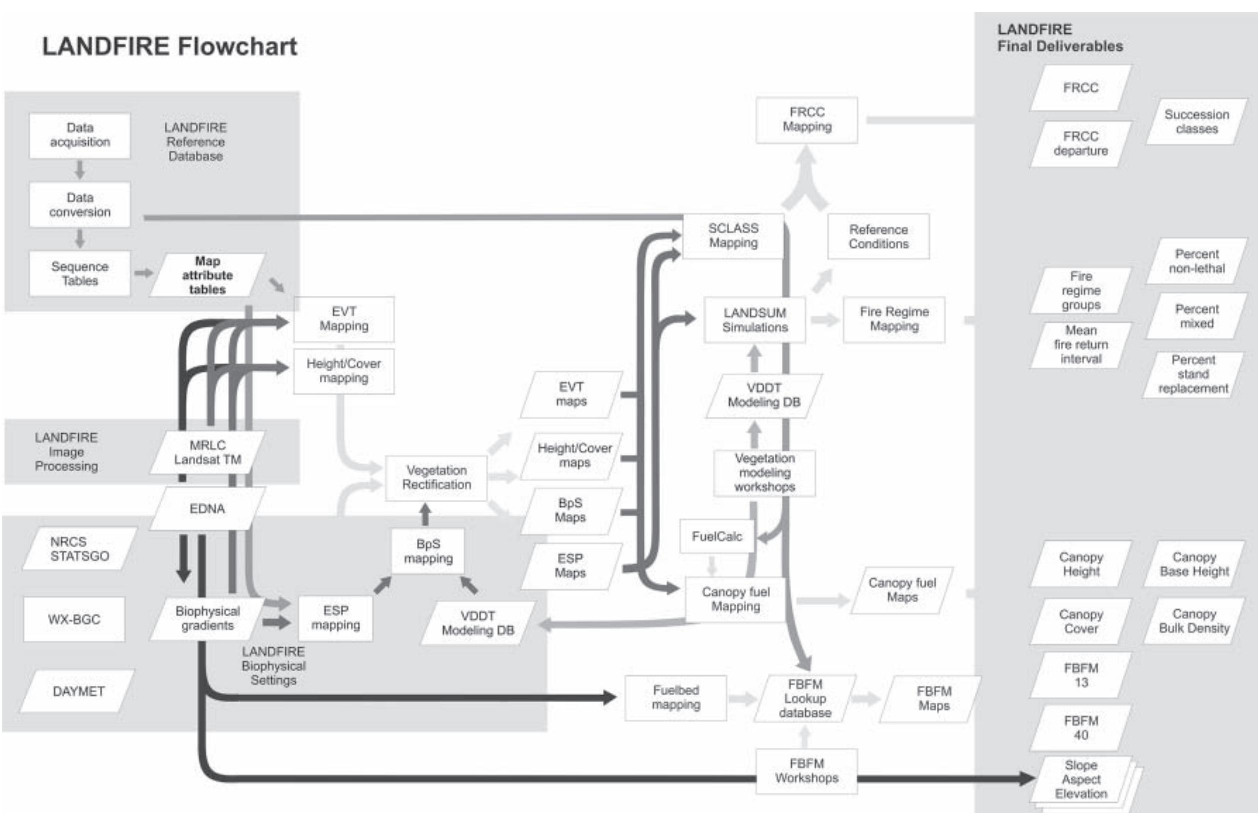

Figure 1—Flow of data, data processing and final products of the LANDFIRE project. Note the dependency of the fuels products on upstream LANDFIRE layers.

reference database for the first 16 mapping zones (fig. 2). Once each plot is converted to a common format, it is keyed to an existing vegetation type (EVT) and environmental site potential (ESP) using sequence table classifiers based solely on floristic composition. A main feature of the reference database for fuels mapping is the inclusion of a suite of predictor variables. These predictor variables form the basis for the landscape prediction models developed for mapping canopy fuels.

Predictor variables fall into one of four categories including; 1) imagery, 2) DEM and associated derivatives, 3) biophysical gradients, and 4) other LANDFIRE layers.

The LANDFIRE program uses the satellite imagery from the Multi-Resolution Land Characterization (MRLC) 2001 project (Homer and others 2004). This system divides the nation into separate mapping zones (fig. 2). There are two key elements resulting from this study that are used by LANDFIRE. First, the LANDFIRE project uses the same mapping zones as those created in the MRLC 2001 project. Second, LANDFIRE uses the satellite imagery that was painstakingly mosaicked for each zone for the conterminous U.S. The essential characteristics of this satellite imagery database are; 1) image dates (time of acquisition) range from 1999 – 2003; 2) imagery is supplied by the ETM sensor, and 3) each mapping zone has three sets of associated imagery including leaf-on, spring and leaf-off. A full description of these data is available in Zhu and others (2006).

The biophysical gradients are derived from WXBGC (Keane and others 2002), a modified version of the ecosystem simulation model, BiomeBGC (Running and Gower 1991; Thornton and others 2002). The meteorological data used to drive WXBGC come from the DAYMET meteorological database, which comprises interpolated surfaces of daily meteorology observations (Thornton and others 2002). In addition to these gradients, a suite of terrain variables such as DEM, slope and aspect are used.

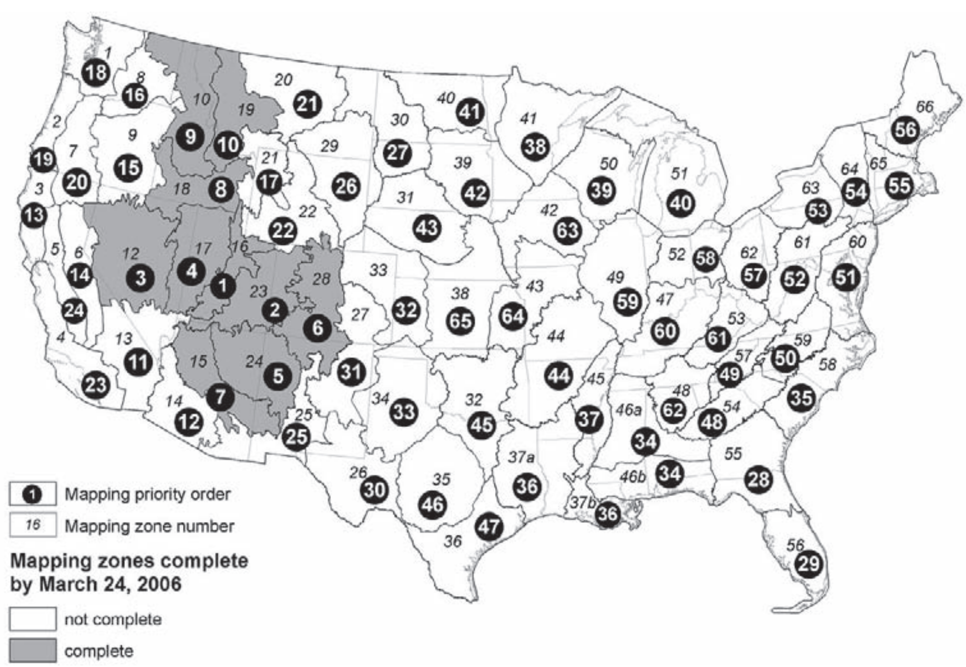

Figure 2—Multi-Resolution Land Characterization (MRLC) mapping zones used by LANDFIRE. Numbers in bold circles represent zones completed as of 5 April, 2006.

Other LANDFIRE Layers—The fuels mapping process relies extensively upon EVT, existing vegetation cover, height and, to a lesser degree, ESP. The EVT and associated structural attributes are produced by Earth Resources Observation Systems (EROS), a United States Geological Survey LANDFIRE partner, while ESP is created at the Missoula Fire Sciences Laboratory.

The EVT depicts the dominant Ecological System (Comer and others 2003) currently present at each 30 m pixel. Each field plot is assigned a life-form and ecological system class, and this information is then used to train decision tree models (Quinlan 1993) using imagery, topographic, and biophysical data (Zhu and others 2006).

Existing vegetation canopy cover, as defined in the LANDFIRE project, represents the average percentage of dominant life-form, non-overlapping canopy cover for each 30 m pixel. A life-form stratification is used to develop independent canopy cover for tree, shrub, and herbaceous life-forms. Canopy cover for the shrub and herbaceous life-forms is developed through use of field plot information in the reference database combined with imagery, topographic, and biophysical data to train regression tree models (Quinlan 1993), while tree canopy cover is developed by procedures employed for the National Land Cover Dataset (NLCD) effort (Homer and others 2004). The final existing vegetation cover dataset is comprised of nine, 10 percent incremental classes ranging from 10 to 100 percent.

Existing vegetation height represents the average height of the dominant life-form for each 30 m pixel. Field plot height measurements, in addition to Landsat imagery, topographic, and biophysical spatial data, are used to train decision tree models that predict existing vegetation height. Continuous tree, shrub, and herbaceous height field data are grouped into 3 to 5 discrete classes, depending on plot height ranges and data availability, prior to being modeled. Prior to dissemination on the National Map (http://nationalmap.gov [last visited 24 March, 2006]) as fuels layers, existing vegetation height and cover are converted to the canopy height (CH) and canopy cover (CC) products. These differ from the existing vegetation height and cover products because the thematic classes are converted to ordinal, biologically meaningful values so that they can be used directly in a fire behavior processor (Finney 1998; Scott 1999). In addition, the CH and CC products only represent cover and height of forested systems, as all herbaceous and shrub areas are coded as 0.

The environmental site potential (ESP) represents the vegetation that could be supported at a site based on the biophysical environment. Map units are named according to NatureServe's Ecological Systems classification (Comer and others 2003). As used in LANDFIRE, map unit names represent the natural plant communities that would become established at late or climax stages of successional development in the absence of disturbance. The ESP is similar in concept to other potential vegetation classifications in the western United States, including habitat types (for example, Daubenmire 1968; Pfister and others 1977).

Fuels Mapping

Fire Behavior Fuel Models—Prior to creating maps of fire behavior fuel models (here referred to as FBFM), LANDFIRE fuelbeds are created using the spatial intersection of EVT/CC/CH/ESP. Every unique combination identified during this process is assigned a fire behavior fuel model. Use of these four variables for identifying fuelbeds is appropriate because it enables maps of fire behavior fuel models to be inferred from vegetation. Existing vegetation type yields information about the type of litter and ultimately, the vegetation that will most likely carry the fire. Canopy cover permits inference of the nature of the understory. For example, in more open canopy situations a greater preponderance of understory vegetation, such as shrubs and herbs is expected. Canopy height can further help the distinction between FBFM's. For example, a grass existing vegetation type will probably burn more like a fire behavior model 1 (Anderson 1982) if it is short, whereas if the grass is tall and dense, for example ≥ 1 m, it will likely be categorized as a FBFM 3 (Anderson 1982). The environmental site potential is infrequently used to distinguish relatively more xeric fuelbeds from those that are relatively more mesic.

Using this information, rules can be created that divide these ranges of possibilities into several categories for each EVT based on expected fire behavior. For example, the assumption can be made that there are two general kinds of fire behavior typically observed in a Great Basin pinyon-juniper environment. The first is a creeping fire with low flame length and rate of spread. This situation often occurs on relatively more dense stands with high canopy cover and low fuel moistures. The other type of fire behavior is more active, with higher rates of spread and flame lengths. This type of behavior is typically observed in relatively more open stands, in high winds, where herbaceous species are denser and shrubs such as sagebrush are interspersed with the larger pinyon pine and juniper.

With this logic, several rulesets can be derived from our example stand of pinyon-juniper (table 1). Each ruleset is subsequently assigned two fire behavior fuel models; one from Anderson (1982) and one from Scott and Burgan (2005). After these preliminary assignments are made they are refined and reviewed by local fire and fuel managers during fire behavior fuel model assignment workshops. After fuelbeds are reviewed, they are linked to a layer in a GIS and fuel model maps are created. After each fuel model map is created it goes through a separate cycle of review by local fire and fuel specialists with revision as appropriate. This second revision process differs from the assignment workshops because it focuses on the spatial expression of the rulesets created by experts during the assignment process. These workshops are a critical part of the LANDFIRE process because they permit collaboration between specialists, with knowledge about their area, and LANDFIRE scientists.

Canopy Base Height and Bulk Density—Canopy base height (CBH) is defined as the lowest point in the canopy at which there is sufficient available fuel for propagating the fire vertically, while canopy bulk density (CBD)

Table 1—Example LANDFIRE fuelbed assignments from a Great Basin Pinyon-Juniper Existing Vegetation Type. ESP is Environmental Site Potential.

Fuelbed #	Cover (%)	Height (m)	ESP	FBFM13[1]	FBFM40
1	0 - 50	Any	Xeric	6	SH1
2	0 - 50	Any	Mesic	2	GS2
3	50 - 100	≥ 3	Any	8	TL1
4	50 - 100	≤ 3	Any	6	SH1

[1]FBFM13 and FBFM40 are fire behavior fuel models from Anderson (1982) and Scott and Burgan (2005) respectively.

refers to the mass of available canopy fuel per unit canopy volume (Scott and Reinhardt 2001). These canopy characteristics are most often used to determine expected crown fire activity for a stand or larger landscape.

The canopy fuels mapping process begins by attributing each plot with estimates of CBH and CBD. These canopy characteristics are computed using FuelCalc (Reinhardt and others 2006, this proceedings). The inputs required by FuelCalc include species, diameter at breast height (d.b.h), canopy height, height to live crown, crown class and trees per acre. These tree lists used as input to FuelCalc are simple attributes to collect but not often recorded in the field with the exception of the Forest Inventory and Analysis (FIA) program. Indeed, 84% of all plots used thus far in the LANDFIRE fuels mapping effort come from FIA data. The FIA data used for this effort range in date from 1978 to 2005, and therefore were obtained using different field methods and plot designs (Bechtold and Scott 2005).

These tree lists are ingested by FuelCalc and canopy biomass is computed by linking d.b.h. with total canopy biomass using species allometric equations. Using these equations, total crown biomass is computed and crown fuel is estimated to be that portion of the crown biomass that may be consumed by the flaming front of a passing fire (≤ 0.6 cm. [¼ in.] dia.). This fuel biomass is apportioned through the canopy of the stand according to the nature of the stand being investigated. From this CBD profile the maximum value is chosen to represent the stand. Likewise, the CBH is defined as the lowest layer in the canopy at which the CBD is ≥ 0.012 kg m^{-3} (0.0007 lb ft^{-3}).

The goal of the canopy fuels mapping effort is to predict CBH and CBD across each LANDFIRE mapping zone by relating these attributes to the plethora of predictor variables available for each zone. These predictions derived in this manner are referred to as the FuelCalc — derived estimates of canopy characteristics. This distinction is significant to later discussions.

The statistical models used to spatially predict CBD and CBH are formulated using the commercially available regression tree, machine-learning algorithm, Cubist (© Rulequest Research 2004) (Quinlan 1993; Rulequest Research 2006). Cubist offers a fast, efficient and relatively accurate approach for building regression tree models that can be applied to large areas (Huang and others 2001; Xian and others 2002). Other salient features of Cubist are discussed in Zhu and others (2006) and Keane and others (2006).

The CBH and CBD regression tree models are evaluated using a 10-fold cross validation procedure (Shao 1993). Different combinations of variables are tested until a consistently low cross validation error rate is observed. Once a suitable regression tree model has been formulated, it is applied spatially using a suite of tools developed in support of the NLCD project (Homer and others 2004; Vogelman and others 2001). These tools were specifically designed to integrate and interpret regression trees formulated using Cubist with the ERDAS Imagine image processing system (Erdas Imagine 2006) (© ERDAS, Inc. 2001).

The landscape predictions of CBH and CBD are then subsequently qualitatively and quantitatively evaluated. Quantitative evaluations include comparisons of CBD with the LANDFIRE canopy cover and satellite imagery. Canopy bulk density is strongly related to canopy cover (fig. 3). Thus, logical relationships between canopy bulk density and canopy cover should be observed in the LANDFIRE products. To evaluate these relationships, zonal statistics are performed such that the mean CBD is computed for each canopy cover class. In a similar manner CBH is evaluated against canopy height for each mapping zone.

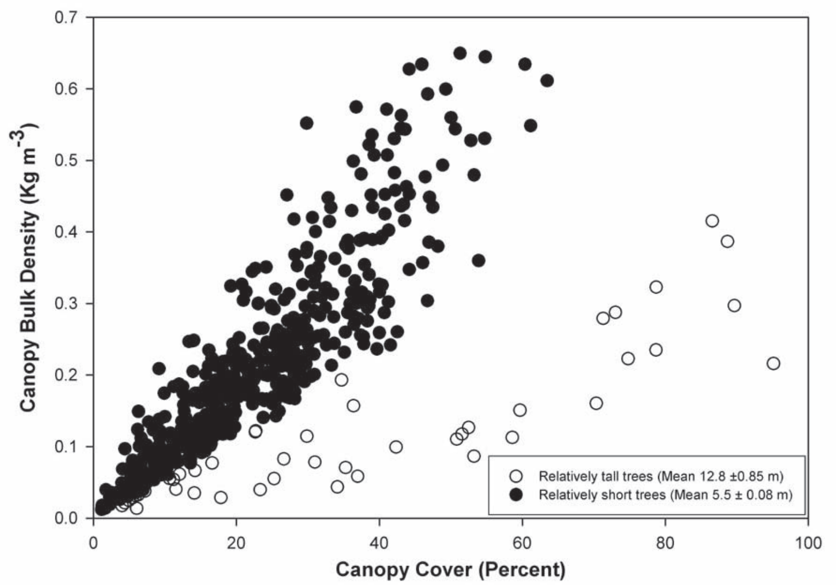

Figure 3—Relationship between estimated canopy bulk density (kg m^{-3}) and canopy cover (percent) from FuelCalc for Mapping Zone 12. Black dots represent relatively short trees (average of 5.5 m with standard error of ± 0.08 m) (usually *Juniperus* spp.), while open circles represent relatively taller trees (average of 12.8 m with standard error of ± 0.85 m).

Other quantitative methods of evaluating the canopy fuel products include comparisons between the frequency of CBH and CBD from the plot data with that of the predicted values in each layer. One might expect a consistent pattern in the numerical distribution between plot and image data, provided that the field plots sufficiently cover the range of variability observed in a mapping zone. For example, if 50 percent of the field plots fell below a bulk density 0.12 kg m^{-3}, then a similar finding in the predicted values for a mapping zone would be expected.

These quantitative methods are combined with extensive visual inspections for obvious errors. While not statistically rigorous, these methods yield valuable guidance and insight as to the appropriate predictor variables and subsequent regression tree formulations that should be used. As a result of these processes, a predictive regression tree model may undergo significant revision for a mapping zone prior to completion of the final product.

Identifying and Filling Areas of Snow, Cloud and Shadow—Although the MRLC project carefully selected scenes of imagery to eliminate clouds, there are still a few small areas where it was not possible to get a totally cloud free scene. Areas contaminated by snow, cloud and shadow are identified in each mapping zone using maximum likelihood supervised classification techniques implemented in Erdas Imagine. Any pixel in a mapping zone dominated by snow, clouds or shadow will be filled using one of two values. These "fill" values are generated using plot data by computing mean CBH and CBD for each EVT/ESP (Stage 1) and EVT (Stage 2) combination. The "filling" process occurs in two stages. Stage 1 filling draws from the database of mean CBH and CBD for each EVT/ESP combination. Use of Stage 1 filling is preferable because it maintains more spatial heterogeneity than the stage 2 filling. However, it is not always possible to use Stage 1 filling because not every EVT/ESP combination on the landscape has plot data with which to compute a mean CBH or CBD. In these instances, the simpler, mean CBH or CBD by EVT is used. Finally, if there is an EVT found in a mapping zone for which there are no plot data to compute a mean CBH or CBD, then the prediction is not altered from its original state (as computed using regression tree formulae) regardless of the error associated with that prediction.

Obtaining Canopy Base Height From an Expert System—Canopy base height is used to aid in predicting surface to crown fire transition. Thus, it is a critical parameter for accurate simulation of crown fire activity. For maximum effectiveness, however, canopy fuels should not be developed independently of surface fuels or illogical combinations might occur (Keane and others 2001). In recognition of the need to convolve CBH estimates with each LANDFIRE fuelbed, an expert system was developed to crosswalk these entities to permit crown fire simulation.

To accomplish this task a series of fire behavior and fire management experts were asked to estimate conditions under which each appropriate LANDFIRE fuelbed would transition from a surface to a crown fire. The expert panel was shown a picture and a description of each fuelbed and then asked to identify specific environmental criteria under which, in their experience, they had observed transitions from surface to crown fire. These fuelbeds combined with the environmental criteria obtained from the experts were fed into a spreadsheet analysis system with the appropriate functions from FARSITE (Finney 1998) programmed into it. The necessary CBH to permit passive crown fire was computed from this analytical spreadsheet. This dataset is separate from the FuelCalc — derived estimates of CBH described above. Indeed, these expert system canopy base height estimates are specifically designed to be used with LANDFIRE data in fire behavior processors and should not be construed as biologically relevant predictions of CBH across the landscape. Instead, this CBH layer simply represents a model parameter that is estimated in the context of each LANDFIRE fuelbed.

Fuel Loading Models—The Fuel Loading Models (FLM) represent a unique surface fuels classification that incorporates the variability of fuel loading within and across fuel components. The model classification uses surface components including fine and coarse woody debris (FWD ≤ 7.62 cm [3 in.] and CWD ≥ 7.62 cm respectively), duff and litter. Fuel loading models were created using four generalized steps: 1) collection of fuels data, 2) compute fire effects from fuels data, 3) cluster fire effects predictions into "Effects Groups" (EG), and 4) classify effects groups to create FLM's. Roughly 4,000 plots were used to create these FLM's spanning a large geographic range.

Using these plots, fire effects were estimated using the First Order Fire Effects Model (FOFEM) (Keane and others 1994; Reinhardt and others 1997). Each fuels plot was subsequently clustered into one of ten effects groups based on total $PM_{2.5}$ emissions and maximum surface soil heating (fig. 4). Classification tree analysis was then used to build a rule set to predict each of these effects groups based on FWD, CWD and duff and litter. These FLM's will eventually be spatially mapped through vicarious linkages with vegetation and fuels attributes from the LANDFIRE project. These mapped FLM's will contain the necessary data to parameterize fire effects models such as FOFEM in a spatial manner.

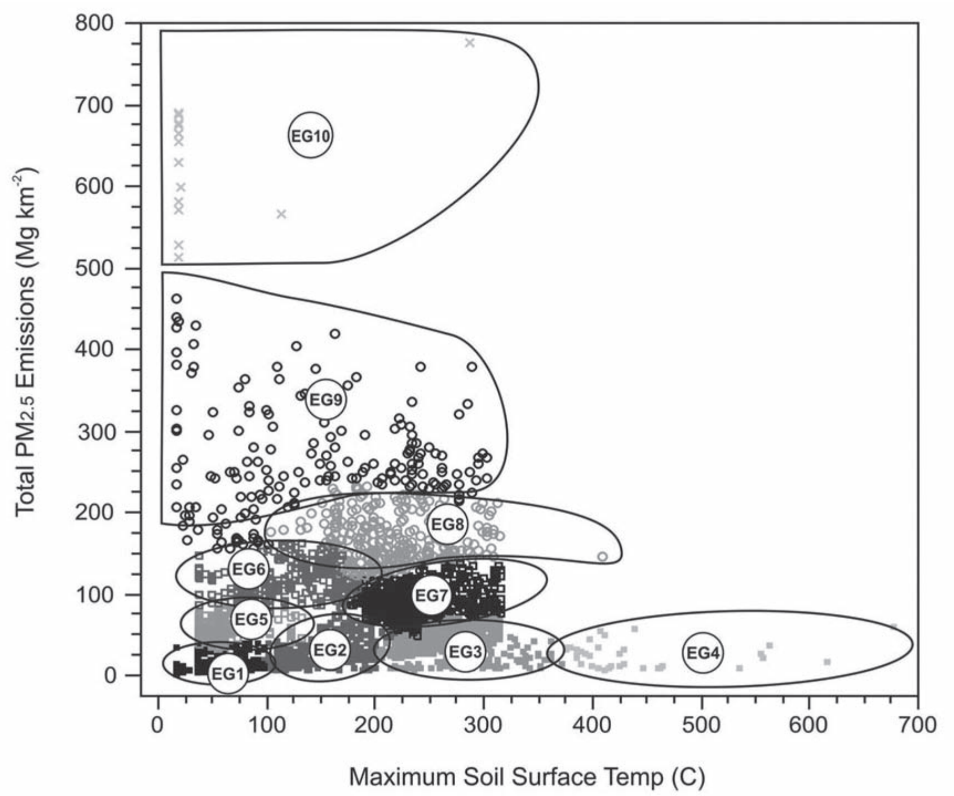

Figure 4—Ten effects groups ordinated by $PM_{2.5}$ (Mg km^{-3}) emissions and maximum soil surface temperature (C).

Discussion

Fire Behavior Fuel Models

Approximately 130 fire behavior and fuels specialists have participated in the LANDFIRE fire behavior fuel model assignment and calibration workshops. This has greatly increased the efficacy of the FBFM layers. For example, a common problem identified with the LANDFIRE FBFM layers is the lack of grass models resulting from invasion by *Bromus* spp. (for example, cheatgrass). As a result, we implemented a procedure, which resulted in millions of acres being updated to grass models due to the preponderance of *Bromus* spp. These and other changes have updated LANDFIRE layers to represent local conditions as near as possible given the constraints of mapping consistency and objectivity. It is notable that the LANDFIRE EVT mapping process is not refined enough to detect stands that have been minimally thinned, which result in accumulation of slash. Thus, it is rare to observe any of the slash models in LANDFIRE data, with one exception. Slash models have been assigned to some LANDFIRE fuelbeds in the southwestern United States. Some stands in this region are late successional decedent stands of *Abies concolor* (white fir) where very high fuel loads (> 60 tons acre^{-1}) of coarse woody debris are observed and blowdown can be several meters thick. The fire and fuel specialists in these areas felt that the fire behavior under these conditions could only be described by slash models, but these situations are relatively rare.

Canopy Base Height and Bulk Density—Examples of the relationships developed during the canopy fuels regression tree analysis are shown in figures 5 and 6. Figures 5 and 6 indicate CBD estimates above 0.4 and CBH estimates above approximately 6 meters are probably not reliable. In general there are not enough plots with large values of CBD or CBH to make a reliable and stable regression tree above these values.

There is an inverse relationship between canopy cover and bulk density in some mapping zones but only in areas of extremely high CC. This non-linear relationship typically only occurs in stands with relatively high CH. This follows the pattern observed in the plot level estimates of CBD and CC (fig. 3). Figure 3 clearly shows two distinct relationships between CBD and CC; one for tall trees and one for short trees.

In comparison to CBD, CBH is more difficult to interpret, map and identify using field based reconnaissance. This is because CBH is more abstract and is not a definitively measurable feature of a stand. Thus, few techniques exist that can be used to asses the true accuracy of these estimates in LANDFIRE data. This is one primary reason for creating the expert system derived CBH estimates. Examples of these expert system estimates are shown in table 2.

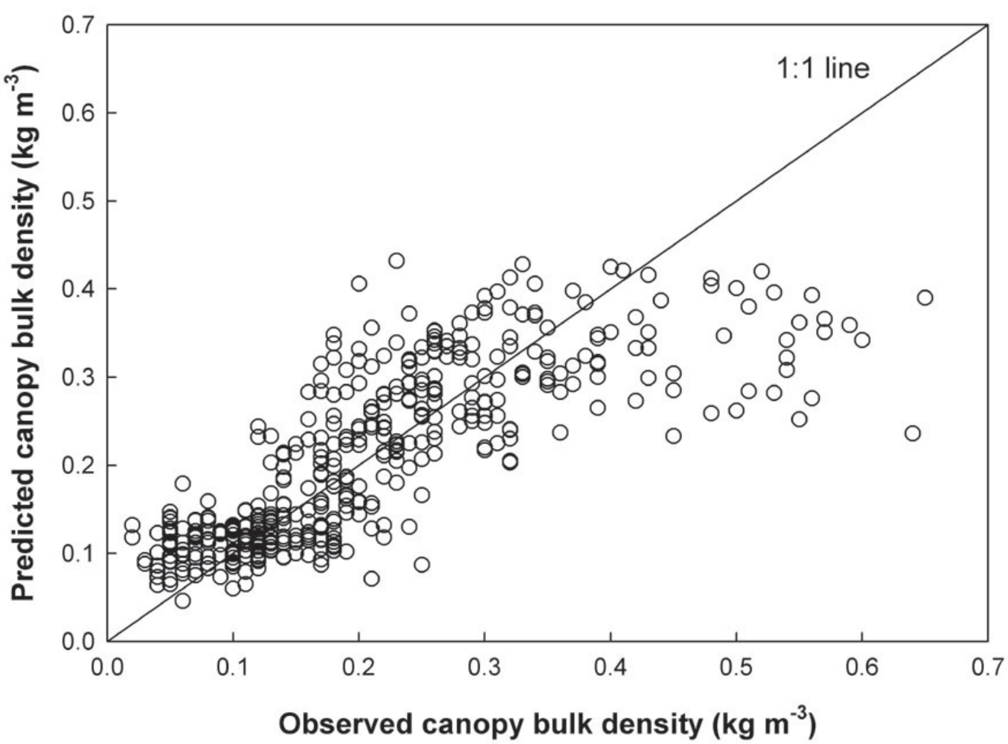

Figure 5—Predicted and observed canopy bulk density (kg m^{-3}) resulting from a regression tree analysis for Mapping Zone 12. Note the asymptotic feature beginning at approximately 0.4 kg m^{-3}.

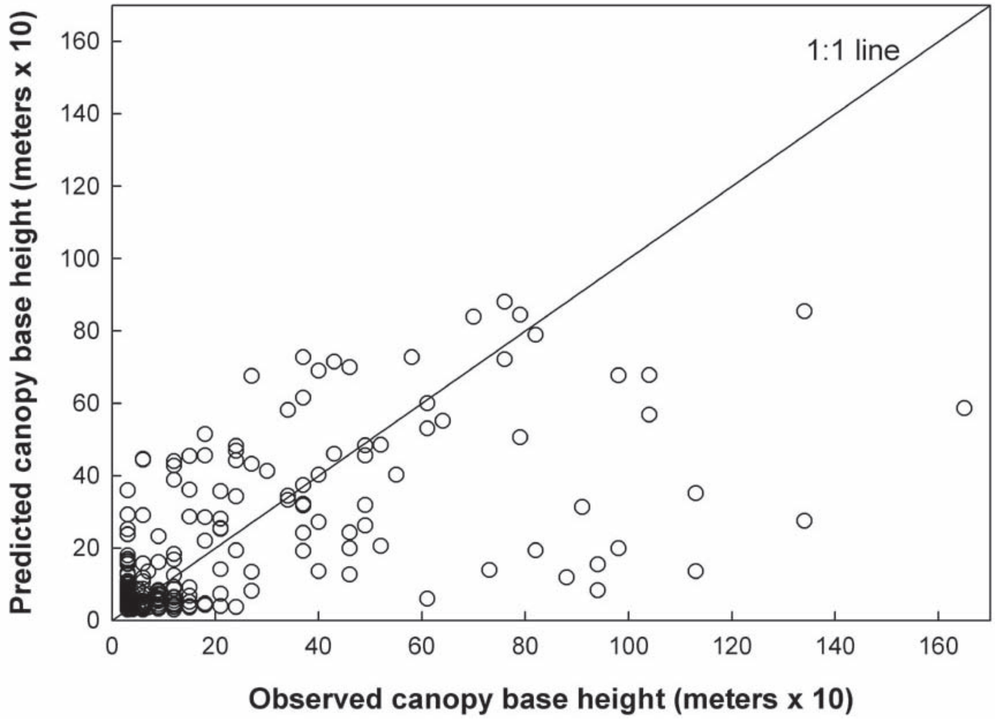

Figure 6—Predicted and observed canopy base height (m) resulting from a regression tree analysis for Mapping Zone 23. Predictions above approximately 6.0 meters are unreliable.

Table 2—Canopy base heights computed using an analytical spreadsheet informed through an expert system. Note that each fuelbed has both Anderson (1982) (FBFM13) and Scott and Burgan (2005) (FBFM40) fuel models. The environmental criteria for this analysis are as follows: fine dead fuel moistures (1,10 and 100 hr time lag fuels) are 4,5 and 6% moisture content respectively; 20 ft. wind speed was estimated as 20 mph.

EVT	Cover	Ht	ESP[1]	FBFM13	FBFM40	CBH13[2]	CBH40[3]
	(%)	*(m)*				- - - - - - *(m)*- - - - - -	
Northern Rocky Mountain Ponderosa Pine Woodland and Savannah							
	≥50	≥ 5	Any	9	TU5	0.29	.71
	< 50	≥ 5	Any	2	TU3	0.075	2.33
	Any	< 5	Any	6	GS2	N/A	N/A
Rocky Mountain Subalpine Mesic Spruce-Fir Forest and Woodland							
	≥ 50	≥ 5	Any	10	TU5	0.34	1
	30 - 49	≥ 5	Any	8	TU1	0.25	0.23
	< 30	< 5	Any	5	SH4	N/A	N/A

[1] ESP is Environmental Site Potential.
[2] Canopy base heights formulated using the Anderson (1982) fuel model.
[3] Canopy base heights formulated using the Scott and Burgan (2005) fuel model.

Use and Limitations of LANDFIRE Fuels Data

The LANDFIRE fuels data layers can be used for applications at varying scales, including project level planning (for example, < 5000 acres), particularly when higher resolution data are lacking. These data are particularly well suited for comparative analyses within and between regions. Thus, it is the responsibility of the user to determine the appropriate scale and usefulness of LANDFIRE fuels data. These fuels layers span all ownerships, a trait not likely to be found in other fuels data sets. These layers are expected to form the baseline data for interagency planning, while local datasets, which cost more and take longer to produce can be used in place of, or in addition to, LANDFIRE data. However, because of their objective and comprehensive nature LANDFIRE data can be used efficiently for such activities as strategic fuels reduction plans, tactical fire behavior assessment and estimating fire effects. These fuels data are the first of their kind because they will seamlessly cover the nation. Any project with this scope will have tradeoffs between quantity and quality. As a result, there is a need for further research for improving the quality of these layers and for assessing their true efficacy. To meet this need we recommend cohesive, scientific, interagency assessments of LANDFIRE fuels data.

Summary

This paper provides a general overview of the LANDFIRE fuels mapping procedures and highlights their interdependency on multiple data sources including other LANDFIRE layers. Fire behavior fuel models are linked with vegetation type and structural attributes based on rulesets devised by local fire and fuel experts. In turn, the spatial expression of these rulesets is evaluated and critiqued in a series of local calibration efforts. Canopy fuels are mapped using predictive landscape modeling by relating a multitude of predictor variables to CBH and CBD in regression trees. These regression trees are subsequently applied across the landscape. Given the nebulous nature of CBH and the dependence on this variable by fire behavior processors, we have devised a strategy to map canopy base height across the landscape using an expert system approach. At national and regional scales LANDFIRE will provide valuable insight for modelers, fire scientists and managers. Finally, we recognize the need for cohesive efforts to assess the efficacy of all LANDFIRE fuels data and hope to initiate this process in the future.

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FUEL3-D: A Spatially Explicit Fractal Fuel Distribution Model

Russell A. Parsons[1]

Abstract—*Efforts to quantitatively evaluate the effectiveness of fuels treatments are hampered by inconsistencies between the spatial scale at which fuel treatments are implemented and the spatial scale, and detail, with which we model fire and fuel interactions. Central to this scale inconsistency is the resolution at which variability within the fuel bed is considered. Crown fuels are characterized by clumps of fuel separated by gaps between needles, between branches, and between trees. A growing body of evidence suggests that this variability plays an important role in how fire spreads. A new system currently in development for representing fuels with higher detail, called FUEL3-D, is presented. FUEL3-D is designed to both facilitate fundamental fuel and fire science research and to provide detailed guidance to managers in the design and evaluation of fuel treatments. Unlike existing fuel models that do not deal with spatial structure or variability within the fuelbed, FUEL3-D represents fuels with spatially explicit detail; individual branches on individual trees are resolved and quantified using fractal geometry and allometric relationships. Fuels can be summarized to 3-D pixels, at any scale, as input to advanced physical numerical fire behavior models such as FIRETEC and WFDS. FUEL3-D can thus be used to represent fuels before and after treatment with much greater detail than has been possible before. Model development, preliminary validation against destructively-sampled crown fuels data sets, and current research inquiries are discussed.*

Background

Current fire management practices and policy emphasize implementation of fuel treatments, such as thinning and prescribed burning, that seek to modify future fire behavior by reducing or altering the fuel bed in some way. A common objective of many fuels treatments is to reduce the likelihood of a fire spreading from surface fuels, such as litter and fine woody debris, to the forest canopy. Fuel treatments must generally be implemented at one time, and actually tested (by a wildfire passing through or near them) at a different time. As substantial resources must be committed to carry out fuel treatments, and conditions at the time the treated area burns are unknown, fuel treatment assessments rely heavily on predictions from computer models. The accuracy of predictions from such models is dependent on the detail with which they represent the main components of the problem, namely, wildland fuels and their interactions with fire.

Spatially explicit models of trees and shrubs have been developed with different levels of detail. The most common applications of such models are light dynamics and plant growth models (see Brunner 1998 and Busing and Mailly 2004 for reviews of several such models, respectively). A common

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approach is to represent trees and shrubs crowns as simple geometric forms, such as cylinders, cones or ellipsoids (e.g., Canham et al. 1999, Kuuluvainen and Pukkala 1987, Pukkala et al. 1993). Such representations are limited to particular scales because detail within the tree crown is not modeled. A much more accurate approach represents plants as fractal objects (Mandelbrot 1983, Godin 2000) and model plant architecture in detail, sometimes extending as far as individual branches, twigs and leaves (Berezovskava et al. 1997, Ozier-Lafontaine et al. 1999, Richardson and Dohna 2003, Godin et al. 2004). Such approaches are particularly relevant to representation of canopy fuels because they successfully capture the natural pattern of clumps of fuel separated by gaps, such as those between needles and between branches.

The clumped nature of wildland fuels is important to fire behavior because propagation of fire is a fundamentally fine scale, spatial process, dependent on the size, shape, composition and arrangement of fuel particles (Burrows 2001) and, particularly, distance between fuel particles (Fons 1946, Vogel and Williams 1970, Weber 1990, Bradstock and Gill 1993). Current management tools used to predict fire behavior, such as BehavePlus (Andrews 2003) and FARSITE (Finney 1998) do not deal with spatial relationships within the fuel bed and cannot be used to reliably assess transitional fire behaviors, such as the change from surface fire to crown fire, or fire-atmosphere interactions that strongly influence the initiation of rapid and intense "blow-up" behaviors which may pose great threats to fire fighter safety (Rothermel 1991, Potter 2002). Fuel treatments can only be assessed with such models as a comparison of average conditions (e.g., Van Wagtendonk 1996). This is problematic because the complex and dynamic nature of fire-fuel and fire-atmosphere interactions may result in cases in which the average conditions either do not actually occur (such as mean crown base height in a two storied tree stand) or do not result in average fire behavior.

In recent years more advanced physics-based, numerical fire behavior models have emerged, such as FIRETEC (Linn et al. 2002, Linn and Cunningham 2005), and WFDS (Mell et al. 2005) that consider spatial variability within the fuel bed, fire-fuel interactions and fire-atmosphere interactions. The detail with which these models address fundamental drivers of fire behavior, as well as the underlying physics basis of the models, facilitates robust prediction of fire behavior and related analyses of fuel treatments at multiple scales.

One of the key limitations in the application of these models is that they require fine scale spatially explicit fuels inputs that are difficult to directly measure in the field, such as 3-D cells describing the distribution of fuel density within a tree. While the fire behavior models are very sophisticated in their treatment of the physics of fire spread and heat transfer, fuels information for wildland fuels of commensurate detail is extremely rare or non-existent. At present no procedures exist by which fuels data measured in the field can be used to develop these inputs or test the accuracy with which fuels are represented. Perhaps even more importantly, no tool exists by which the fundamental properties of wildland fuels can be assessed, quantified and evaluated as to their importance across a range of spatial scales. Wildland fire science will not be able to take full advantage of the advancements that have been made in fire modeling until these knowledge gaps are addressed.

One component of fuel treatment assessments that has not received much attention is the change in microclimate resulting from the treatment. The size, density and geometry of plants affects solar radiation at the forest floor (Reifsnyder and Lull 1965, North 1996, Govaerts and Verstraete 1998) and the interception of rain by the canopy (Helvey and Patric 1965), which both influence fuel moisture (Fosberg and Deeming 1971, Nelson 2002). The canopy structure also influences winds within a stand (Jensen 1983, Oke 1978, Brandle 1980). Fuel treatments may thus result in significant feedback relationships with the microclimate, which may alter the future behavior of fire within a stand in unexpected ways. At present we are greatly limited in our ability to assess the nature and magnitude of these effects.

Objectives

In this paper I introduce a spatially explicit fuel model called FUEL3-D, which can be used to represent fuels in great detail, both as discrete branches and as 3-D cells. This model represents a new concept in fuel modeling, in which fuel beds are described as a collection of discrete elements such as individual trees and branches within trees. FUEL3-D can be used to provide inputs to detailed numerical fire behavior models that account for spatial relationships within the fuel bed and are thus more sensitive to fuel treatments than current operational fire models.

I describe preliminary parameterization for ponderosa pine crown fuels based on destructively sampled crown fuels data and present results of preliminary validation analyses of biomass quantities against independent validation data. I then demonstrate two ways in which fine scale representations of fuels might provide insights relevant to fuel treatment assessments. First, I demonstrate how spatial relationships within the fuel bed influence fire behavior using a three-dimensional physical fire behavior model, WFDS (Mell et al. 2005). Second, using ray-tracing procedures I demonstrate how the spatially resolved structure of wildland fuels can be used to simulate the influence of the forest canopy on light dynamics at the forest floor, an important component of surface fuel moisture dynamics as well as vegetative response to fuel treatments. I conclude with discussion of how modeling fuels at fine scales fits into the larger picture of fire management.

Methods

Parameterization of the FUEL3-D Model for Ponderosa Pine

As the precise number, size and positions of individual branches composing the crown of an individual tree will generally never be known, it is necessary to simulate this structure. This is done on the basis of relationships identified from field data describing biomass quantities and geometry within the crown.

Field Data and Analysis—Detailed crown fuels data were collected through a destructive sampling crown fuels study in five locations in the western United States in 2000 and 2002 (Scott and Reinhardt 2002). In each study location, field crews systematically measured, removed, dissected and weighed individual branches for each tree in five stands destructively sampled between 2000 and 2002 (Scott and Reinhardt 2002). Tree level measurements included height, height to crown base, health status, canopy class (dominant, codominant etc.), coordinates of the tree stem and diameter at breast height (1.35 m, DBH). Branch level measurements included branch basal diameter, height on bole, angle from vertical, total length, width, and weight, separated out by component (woody vs. foliage, live or dead, etc.).

Woody fuels were separated and weighed by fuel moisture lag time size classes, i.e. 1 hour, 10 hour (Fosberg and Deeming 1970). I used tree and branch data measured for ponderosa pine (*Pinus ponderosa*) trees in a dense, single storied stand at the Flagstaff, Arizona field site in this initial development and testing of the FUEL3-D model. Of the original 85 trees, 7 trees with no individual branches, such as broken snags, were excluded from analysis, resulting in a data set of 78 trees and a total of 2207 individually measured branches. The trees were mostly codominant and intermediate trees with diameters ranging from 2.6 to 38.4 cm (mean 17.2 cm) (Figure 1). The majority (80%, 62 trees) of this data was randomly selected for model-building (to develop empirical relationships used in the model), and the remainder (20%, 16 trees) was withheld for validation. An additional 16 ponderosa pine trees measured at the Ninemile, Montana field site for the same study were used to assess how well relationships identified for the Flagstaff data could be applied to ponderosa pine trees sampled at other locations.

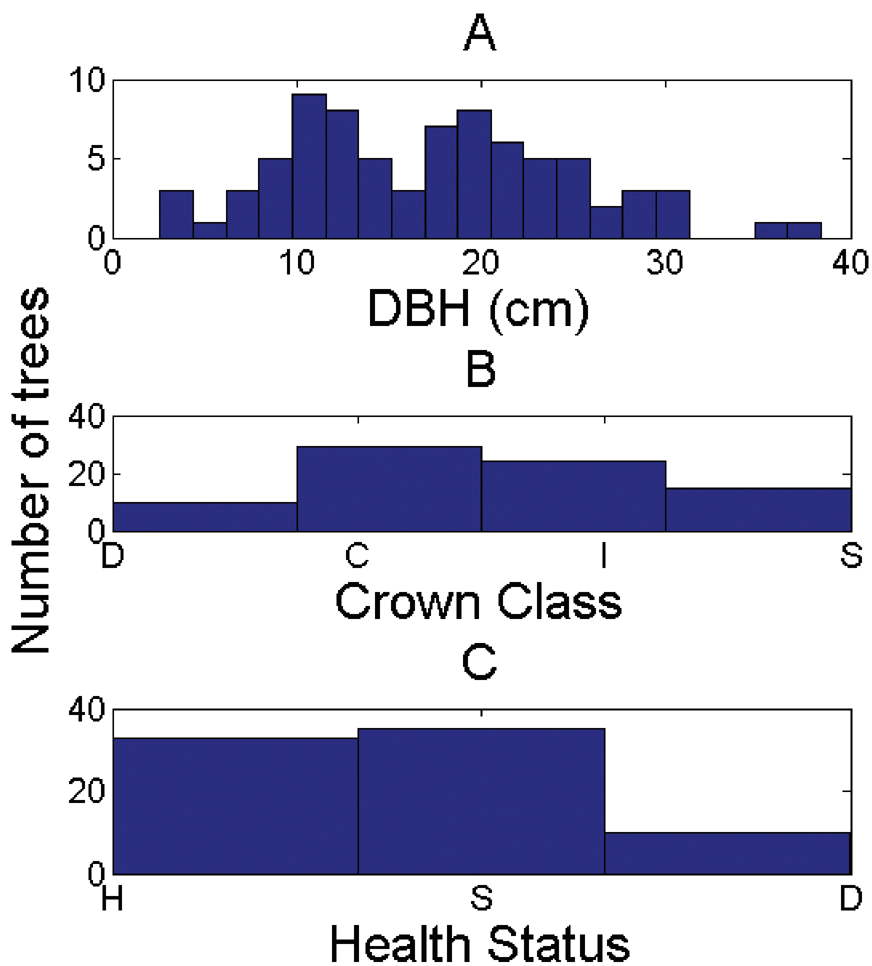

Figure 1—Three plots showing properties of data for the 78 ponderosa pine trees used in this study. All data used were from the Flagstaff field site: A) diameter distribution: B) Crown class distribution: D=Dominant, C=Codominant, I=Intermed, S=Suppressed. C) Health Status: H=Healthy,S=Sick,D=Dying

I supplemented this main data set with additional data collected in 2004 and 2006 in Montana. These data sets included measurements of angles between sub-branches, lengths and diameters of sub-branches as proportion of parent branches, and weights and dimensions of individual clumps of needles. This data in combination with the more extensive crown fuels study data described above provided information adequate for modeling sub-branches and distribution of biomass within a branch.

Using the model-building data I used non-linear regression procedures to predict the total branch biomass, and total foliar biomass for a branch as a function of basal branch diameter. I then used maximum likelihood estimation procedures to fit theoretical Weibull probability density functions (Grissino-Mayer 1999) describing the branch size class distribution of individual branches as a proportion of tree diameter at breast height (DBH) (Figure 2). The Weibull distribution is a flexible continuous positively skewed distribution described by the probability density function

$$f(y) = \left(cy^{(c-1)} / b^c \right) e^{(-(y/b)^c)} \qquad [1]$$

for the range $0 <= y < \infty$, scale parameter, b and shape parameter, c. I assessed model fit for branch size distributions with the Komologorov-Smirnov (K-S) test. Additional analyses (not presented here for the sake of brevity) assessed relationships between the position and orientation of the base of a branch along the tree stem and set upper limits for the total length and width of each branch, all on the basis of branch basal diameter. A summary of parameters used to describe and model ponderosa pine is presented in Table 1.

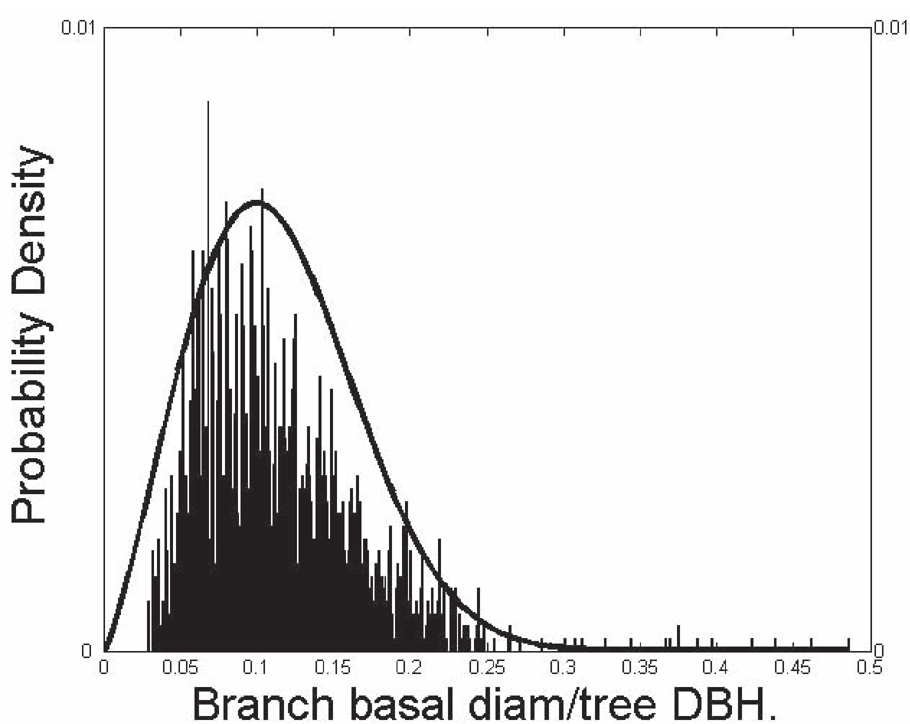

Figure 2—Distribution of branch basal diameters, as proportion of tree diameter at breast height, for 62 ponderosa pine trees destructively sampled near Flagstaff, Arizona. Smooth line shows theoretical distribution fitted on this data.

Table 1—Empirical relationships and parameters used to model ponderosa pine crowns.

Dep. var. (abbrev), units	Indep. var. (abbrev), units	Function type	Equation	Fit
Allometries				
Branch diameter size class distribution[a]		Weibull pdf.	$f(y) = (cy^{(c-1)} / b^c)\, e^{(-(y/b)^c)}$ b = 0.128 c = 2.285	K-S 0.06 p-value 0.0002
Total branch biomass(TB), g	Branch basal diameter(BD),cm	Power $Y = ax^b$	$TB = 27.17 * BD^{2.77}$	$R^2 = 0.96$
Branch foliar biomass (FB), g	Branch basal diameter(BD),cm	Power $Y = ax^b$	$FB = 11.15 * BD^{2.36}$	$R^2 = 0.92$
Geometry				
Total branch width (BW), m	Total branch length (BL,m)	Linear Y = ax	BW = 0.50 * BL	$R^2 = 0.69$
Total branch length (BL), m	Branch basal diameter(BD),cm	Power $Y = ax^b$	$BL = 0.47 * BD^{0.99}$	$R^2 = 0.77$
Angle between branches, degrees	NA	Random, normal pdf.	Mean = 77 stdev = 9	

[a] Branch diameter distribution modeled as a proportion of tree diameter, so y = Branch basal diameter / tree d.b.h. This accounts for the increase in branch diameters as trees get larger.

Simulation of Tree Crowns—Simulation of a tree begins with a measurement of DBH. This is used to predict the size class distribution of branch basal diameters on the basis of analysis described above. Individual branch basal diameters are then sampled from this distribution until the sum of the cross sectional areas of the branches equal the tree cross sectional area. This relationship, first observed by Leonardo da Vinci and later applied in the pipe model theory (Shinosaki et al. 1964), has been shown to be true for a wide range of tree species and is a common basis in fractal models of plant structure (Berezovskava et al. 1997, Ozier-Lafontaine et al. 1999, Enquist 2002). For each branch basal diameter total branch biomass and foliar biomass quantities are then predicted using empirical functions described above. At this point each branch is defined in general terms but has no structure of sub branches.

The structure of sub branches which comprises the total branch is modeled as a series of frustums of a right circular cone, described by two vertices defining the position of the end points, and the radii at each end perpendicular to the line connecting the vertices (Figure 3). The branching structure is assembled using a static fractal model approach (e.g., Ozier-Lafontaine et al. 1999), described only briefly here. An initial segment is defined which represents the first part of a branch up to the point where sub branches form. The dimensions of this branch, along with geometric parameters describing the number of child branches and angles between them are used as the "seed" in a recursive function, common to numerous fractal tree models (Berezovskava et al. 1997, Niklas 1986). The effect of the recursive function is to continue

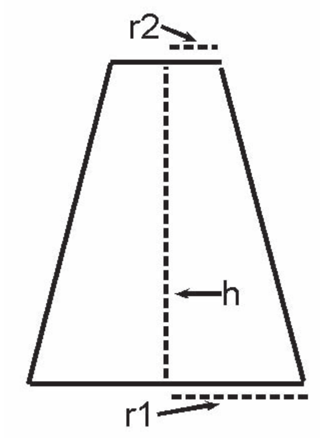

Figure 3—Planar view of a frustum of a cone, defined by length h, large radius R, and small radius r. The frustum of a cone is the basic building block for branches within the FUEL3-D spatial fuel model.

branching until some predefined end condition is met. In this manner each branch extends itself, splits into smaller branches, which themselves split into smaller branches, and so on (Figure 4). The position of each segment in 3-D space, dimensions and orientation and other attributes are written to a list for future use. In this initial configuration of the model branching was stopped when the distal radius of the segment was small enough to be considered a terminal, which represents a clump of needles. A terminal is defined in space as a frustum of a cone but also has additional attributes describing the total number of needles, surface area, foliar biomass etc. For extremely detailed simulations (typically only within a small area) it is possible to replace each terminal with a series of smaller objects. In this manner it is possible to represent detail down to the level of individual needles if desired.

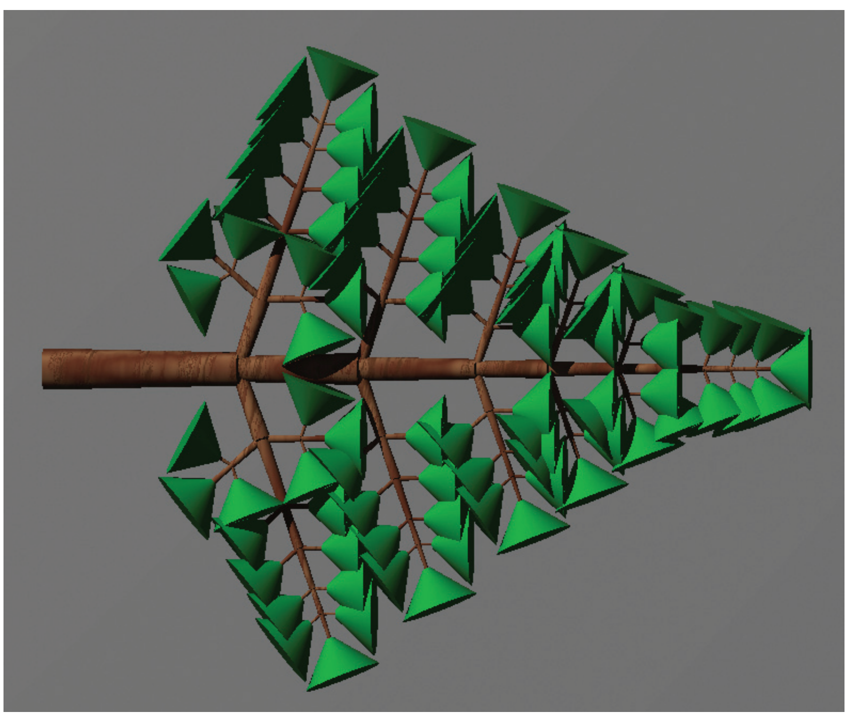

Figure 4—A simulated branch with sub-branches generated with FUEL3-D.

Summarization to 3-D cells—In order to use the fuels data defined as discrete objects in the numerical fire behavior models it is necessary to convert the data to values associated with three-dimensional grid cells (Figure 5). This is accomplished by slicing each branch segment, perpendicular to its main axis into a number of circular cross sections. Each circle is "clipped" along the line of intersection between the plane within which it lies and each of the applicable planes which constitute the limits of the 3-D cell. The area of the resulting, possibly irregular, polygon is stored off in a list. All of these areas are then numerically integrated to calculate the volume of that branch that lies within the particular cell. This procedure is repeated for each cell and for all branch segments. Parts of a branch segment that are cut out of one cell will be accounted for in an adjacent cell. In this manner the total quantities are preserved across whatever spatial scale is desired.

Comparison With Validation Data—Comprehensive validation of a complex model often requires a large number of tests; as the FUEL3-D model is still in active development validation efforts are ongoing. I compared the measured total crown biomass, for the two independent validation sets, against quantities simulated with FUEL3-D (Figure 6). The modeled relationships used in testing were all derived from the Flagstaff model building data set.

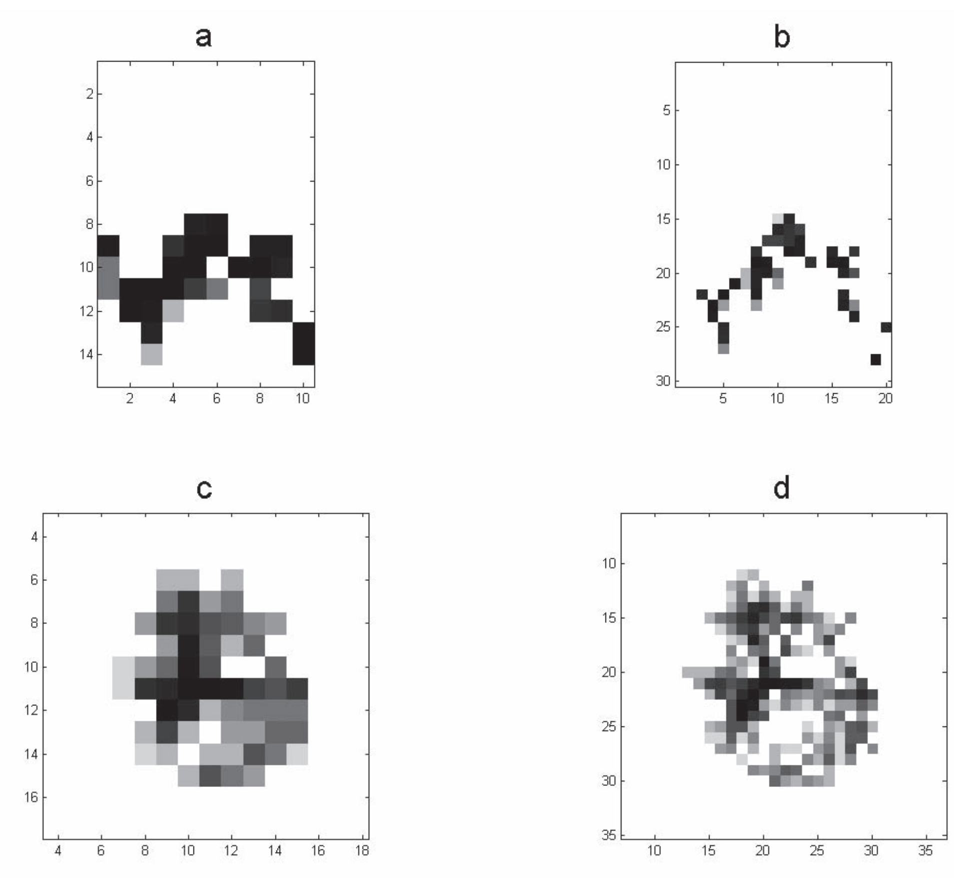

Figure 5—3-D cell representation of density within the crown of a small tree, for two resolutions (columns, left 10 cm cells, right, 5 cm cells) and two perspectives (rows, top, side view of vertical slice through volume, bottom, overhead view of horizontal slice through volume. Light colors are low values of density within a cell and dark cells are higher values. A) 10 cm cells, side view, vertical slice; B) 5 cm cells, side view, vertical slice; C) 10 cm cells, overhead view, horizontal slice; D) 5 cm cells, overhead view, horizontal slice.

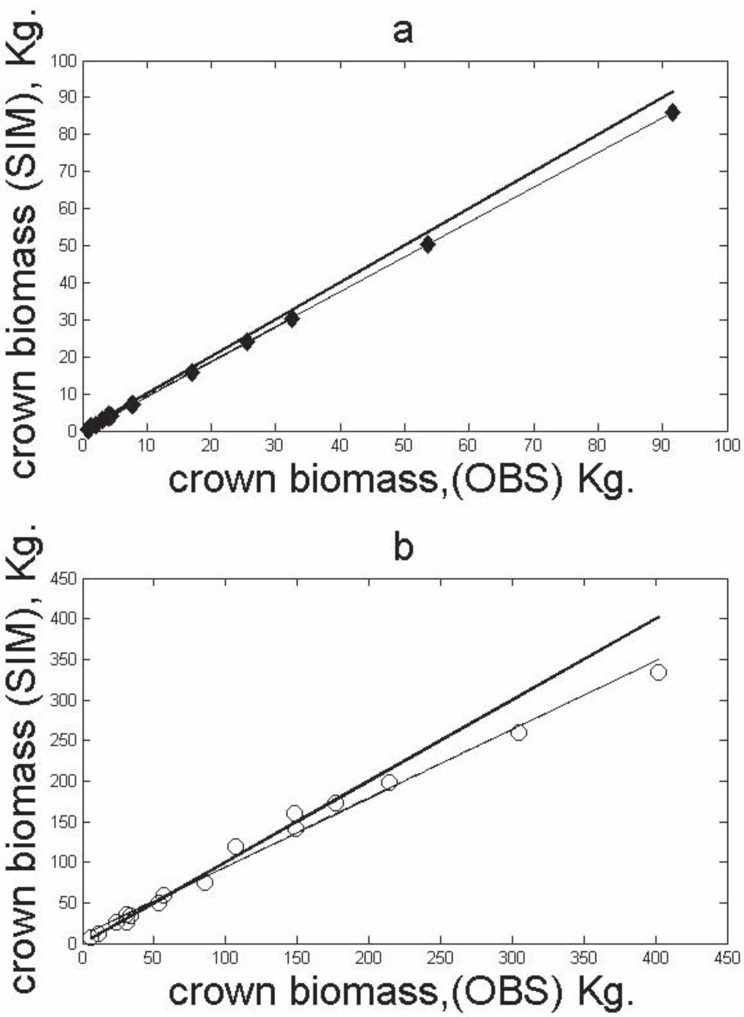

Figure 6—Comparison of measured total crown biomass (X axis) against crown biomass simulated with FUEL3-D (Y axis) for 16 trees used as independent "holdout" validation data from the Flagstaff site (a), and from the Ninemile site (b). Neither set of trees was used to construct modeled relationships. Solid lines in both figures represent the 1:1 line, while thinner lines are fit to the data. Correlations for fitted lines were 0.94 (a) and 0.98 (b), but slopes less than 1.0 show that modeled relationships underpredict biomass for larger trees in both sites.

Simulating Fire and Fuel Interactions—I demonstrate how detailed representations of fuel structure may provide insights to fire and fuel interactions with two related simulations using the physics-based fire model WFDS (Mell et al. 2005). The data used as inputs were similar to outputs from FUEL3-D, with values associated with individual 3-D cells, but were somewhat simplified as explicit connections between FUEL3-D and WFDS are still in development. The simulations were set up within a very small area similar to a wind tunnel in dimensions (8m long x 4 m wide x 4 m wide). For fire computations this area was divided into 64 x 32 x 32 cells, 0.125 m on a side. Within this small spatial domain I simulated a surface fuel bed 0.25 m in depth, 2 m wide and 6 m long, with fuel properties of excelsior (shredded aspen) and a constant moisture content of 6.3%. Three simulated trees were placed with the center of their stems at 2 m, 4.5 m and 6 m along the centerline of this fuel bed (Figure 7). WFDS represents trees and other

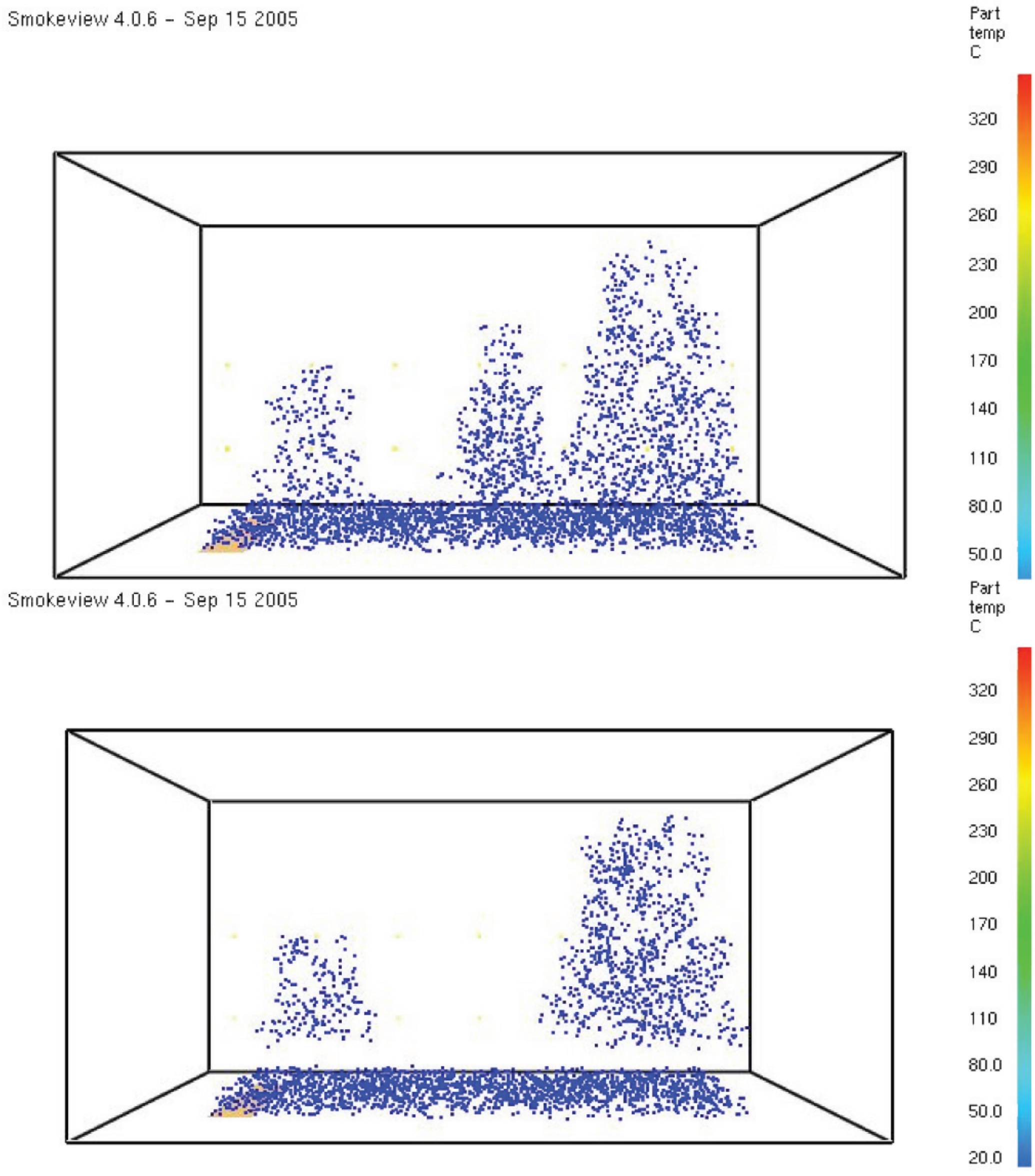

Figure 7—Comparison of two simulations with a numerical fire model, WFDS, and highly resolved at t = 0. Top figure shows "untreated" simulation with three small trees and a surface fuel bed in a wind tunnel. The outer trees are live, with high moistures and the middle tree is dead with low moisture, representing a recently bug-killed tree. Bottom figure shows the "treated" simulation in which the middle dead tree has been removed and lower branches have been pruned to 0.75 m.

elevated fuels as collections of thermally thin particles. Each tree was defined individually with a height, height to crown base, crown radius, and available fuel moisture content. To represent gaps within the crown, the crown for each tree was defined as frustum of a right circular cone. Within the volume of that cone, each cell was either assigned fuels or was empty depending on a random number. The first and third trees were parameterized as with more gaps, to represent more gappy, live trees while the middle tree was parameterized as less gappy and dead, with a much lower moisture content. An ignitor panel was simulated at the left edge of the fuel bed to start the fire. Winds were initialized at zero but were accelerated to a constant 1.5 m/s (3.4 mph) three seconds into the simulations. The first simulation used these fuels with no modifications and represents the "untreated" case. The second simulation represents an extremely simple fuel treatment, consisting of thinning (removal of the dead, middle tree) and branch pruning (removal of fuels in the two remaining trees below 0.75 m). Both simulations were run for a duration of 120 seconds. Graphical outputs from Smokeview, the companion software to WFDS used to visualize WFDS outputs for the two simulations for t = 0, 48, 60 and 72 seconds are shown in Figures 7-10. In these figures, the small particles represent the fuels, the lighter cloud-like structures represent flames (as isosurfaces of heat release rate per unit area, in KJ/m^2) and the darker cloud like structures represent soot density. These simulations were not intended to provide definitive scientific results, as the spatial domains are probably too small to eliminate artifacts arising from the proximity of the boundaries, but simply to illustrate potential applications of numerical fire behavior models in fuel treatment assessments.

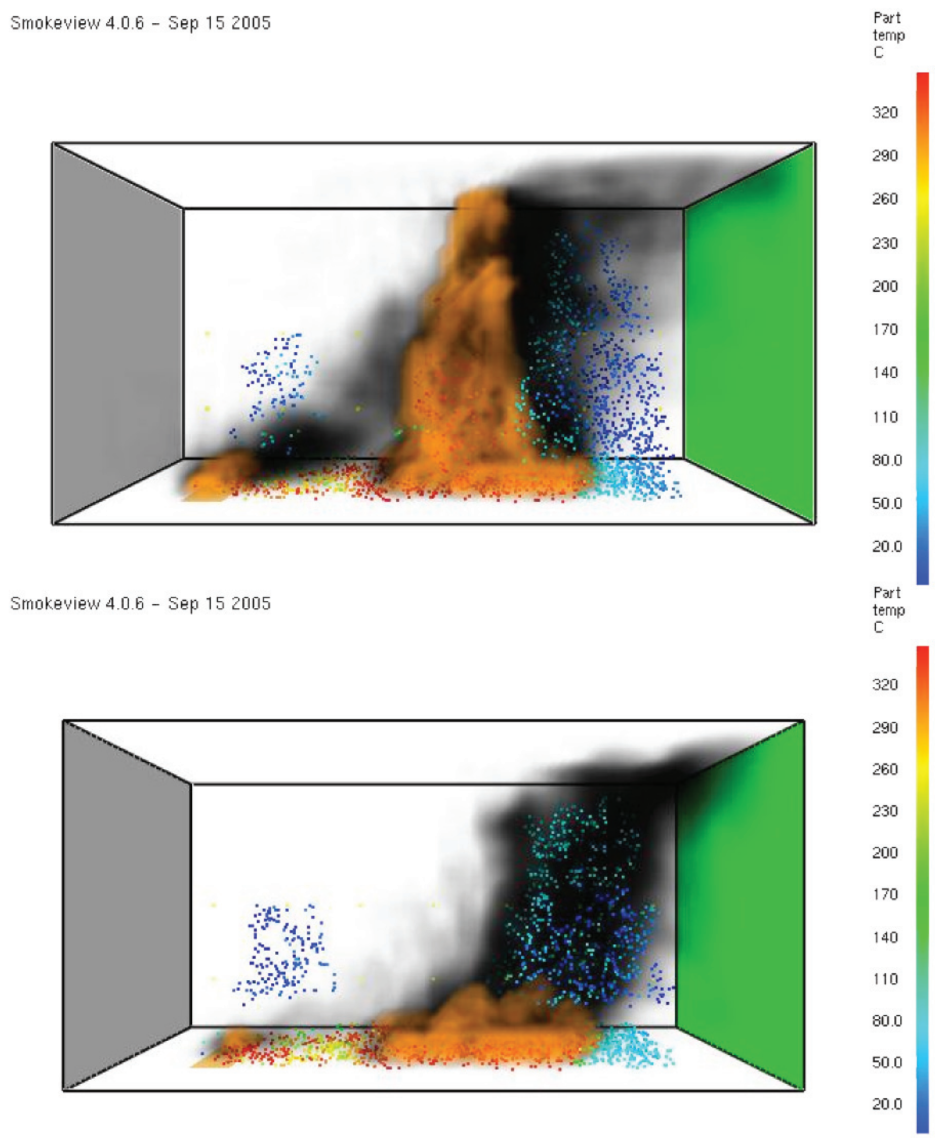

Figure 8—Demonstration of a numerical fire simulation with the Wildland Urban Interface Fire Dynamics Simulator (WFDS), and highly resolved fuels at t = 48 seconds. Surface fuels are burning in both simulations but the middle dead tree in the untreated simulation (top) is burning intensely.

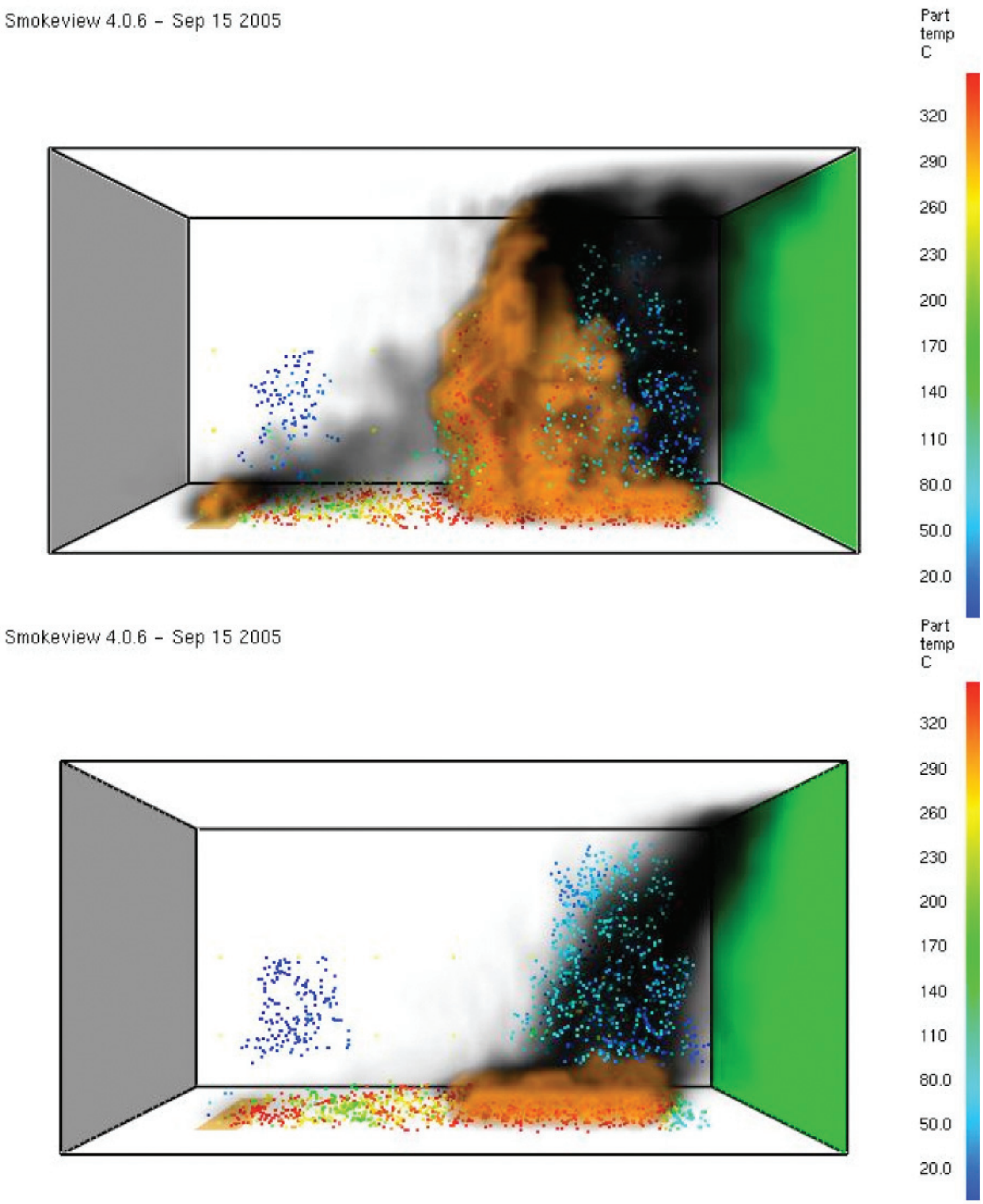

Figure 9—Demonstration of a numerical fire simulation with the Wildland Urban Interface Fire Dynamics Simulator (WFDS), and highly resolved fuels at t = 60 seconds. Surface fuels are burning in both simulations. Heat from the the middle dead tree in the untreated simulation (top), as well as from the surface fuels, has caused the tree at right to ignite. In the "treated" simulation (bottom) the tree at right is scorched from below but does not ignite.

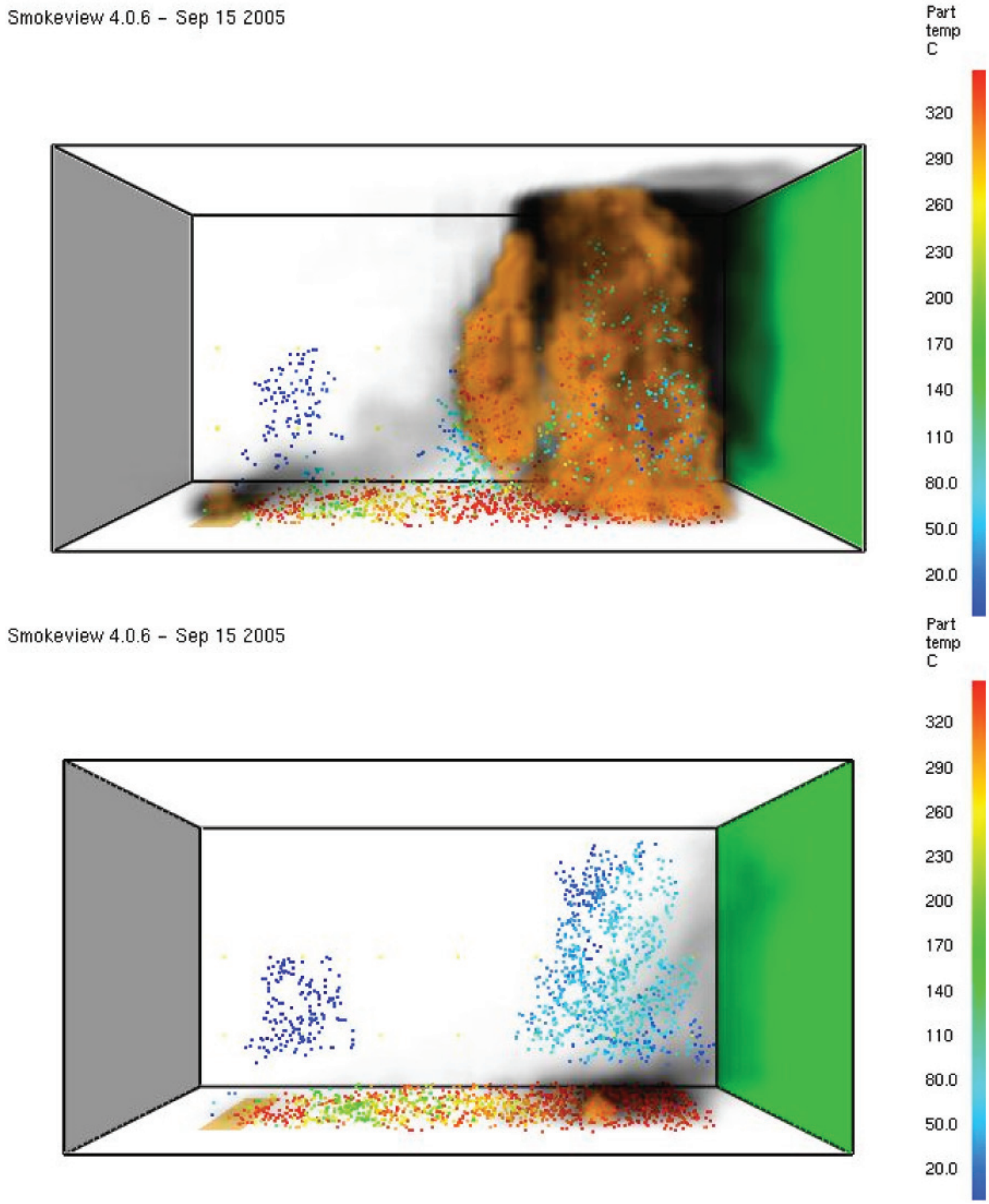

Figure 10—Demonstration of a numerical fire simulation with the Wildland Urban Interface Fire Dynamics Simulator (WFDS), and highly resolved fuels at t = 72 seconds. Surface fuels are burning in both simulations. Heat from the the middle dead tree in the untreated simulation (top), as well as from the surface fuels, has caused the tree at right to ignite, and it continues to burn intensely. In the "treated" simulation (bottom) the tree at right is scorched from below but does not ignite.

Simulating Canopy Shading—To demonstrate the application of fine scale spatial representation in assessing impacts to the microclimate I used ray tracing procedures (North 1996, Govaerts and Verstraete 1998, Brunner 1998) to simulate the shadows cast by a single tree modeled with FUEL3-D. The tree was parameterized with data from the Flagstaff field site but arbitrarily located in Missoula, Montana, at a point in space (Latitude 46.5 North, Longitude 114.0 degrees West, Missoula, Montana) and at two points in time 30 minutes apart (June 21, 2005, 14:20 and 14:50 local time) (Figures 11 and 12). Ray tracing is a spatially explicit approach for light modeling which samples beams of light between the light source (the sun) and a given object and thus is capable of representing shadows and other behaviors related to light with great detail, both in space and in time.

Figure 11—Visualization of a medium sized ponderosa pine tree modeled with FUEL3-D. The shadow of the tree, modeled with ray-tracing procedures, is shown at left.

Figure 12—Visualization of the same tree as in Figure 11 but 30 minutes later. The shadow of the tree, modeled with ray-tracing procedures, is shown at left, has moved slightly as the position of the sun changed.

Results

Field Data Analysis

Several relationships were identified from analysis of the field data (Table 1). Two sets of relationships are described: allometric relationships which relate easily measured quantities on a tree, such as DBH, to properties within the tree, such as the size class distribution of branches, and geometric relationships which describes properties and proportions. The size class distribution of individual branches on a tree, as a function of tree DBH, was positively skewed and fit well with the Weibull distribution as measured with the K-S statistic (Figure 2, Table 1). Branch biomass quantities were strongly related to branch basal diameter with power law relationships. These relationships provide the basis for the simulation of canopy structure of ponderosa pine trees.

Comparison/Validation

Biomass quantities simulated with FUEL3-D compared reasonably well with both validation data sets, with correlation coefficients of 0.94 for the independent holdout data for Flagstaff site and 0.98 for the Ninemile site data (Figure 6). Slopes of linear trend lines fit to the validation data were somewhat less than 1.0 (0.95 for Flagstaff and 0.86 for Ninemile), indicating that biomass quantities for larger trees might be underestimated. The Ninemile data consisted of generally larger trees, and a very different biophysical setting, so it is difficult to determine whether the underestimation observed for larger trees is purely a function of tree size or if it has some interaction with differences between sites.

Numerical Fire Simulations

The two simulations illustrate how spatial relationships within the fuel bed can result in differences in fire behavior. The two simulations had identical environmental conditions (wind speeds and fuel moistures) but removal of the center dead tree and elimination of lower branches on the remaining trees (Figure 7) resulted in differences in fire behavior between the two simulations. Figures 7-10 show the progression of the two simulations at t = 0, 48, 60 and 72 seconds, respectively. At t = 48 (Figure 8) the center tree in the untreated simulation (top) is engulfed in flame while in the treated simulation, the fire is confined to the surface fuels. At t = 60 (Figure 9), flames are moving into the crown of the large tree at right in the untreated simulation (top); at t = 72 that tree is actively flaming throughout the crown (Figure 10). At these points in time in the treated simulation the fire is burning underneath the crown of the rightmost tree but does not ascend into the crown.

Simulating Crown Shading—Visualizations at two points in time 30 minutes apart (Figures 11 and 12) show the detail with which individual trees and their shadows can be modeled. In full sun conditions, shadows from trees significantly reduce the direct solar radiation received at a shaded point on the ground. Direct solar radiation is a key driver of dead fine fuel moisture, raising the fuel temperature, heating the boundary layer and accelerating evaporation (Nelson 2002). Modeling shadows from individual trees may thus be applied to assess spatial variability in surface fuel moistures and changes in such patterns arising from fuel treatments.

Discussion

The models which form the basis of our current operational capacity to assess fuel treatments, namely, the fire behavior model BEHAVE (Rothermel 1972) and the stand growth model PROGNOSIS (Stage 1973), were developed at a time when many processes in combustion science and plant growth were poorly understood, and when both computational resources, and the data which could be used as inputs to predictive models were limited. Advances in computing resources, information technology and geospatial applications such as GPS, GIS and remote sensing change the nature of what is possible in assessing fuel treatments. New sensors such as LIDAR make it possible to measure individual tree stems and branch heights (Henning and Radtke 2006), individual crown diameters (Popescu et al. 2003) and estimate other stand characteristics (Nelson et al. 1988). The continuing development of such technologies suggests that detailed modeling of fire and fuels will only become more accessible to the wildland fire community as time goes on.

The FUEL3-D model is still in development and should be viewed as a work in progress. The same holds true, to a lesser degree, for the numerical fire models themselves which represent a rapidly advancing but still emerging field in fire science. Continuing development of the FUEL3-D model will provide avenues by which important knowledge gaps regarding wildland fuel properties, microclimate-fuel dynamics, fire-fuel interactions and fire effects can be addressed. Although the model is currently more appropriate for research use, a management appropriate configuration will be developed as soon as the underlying structure of the model is sufficiently mature.

The ability to represent the spatial structure of vegetation in detail across a range of scales will facilitate improvements in our understanding of fundamental fuels science. Fuel beds can be constructed describing any configuration of trees and shrubs of any size. By building fuel beds from individual trees and shrubs (and associated surface fuels), loss of relevant detail and scale-dependencies associated with fuel classifications is avoided (Sandberg et al. 2001). At present there is no way that fundamental wildland fuel properties, such as surface area to volume ratio, the size distribution of particles or distribution of mass within a tree crown, can be easily calculated. With FUEL3-D these quantities can be calculated from the simulated structure, tested and calibrated. The flexibility with which FUEL3-D can represent the architecture of trees and shrubs makes it possible to develop species-specific fuel models. Differences in crown architecture between species likely play key roles in how fire burns through a stand and how that stand responds to fuel treatment over time. This provides stronger linkages between silviculture, ecosystem function and fuel management such that fuel treatments can be considered not only in terms of their potential impacts on fire behavior but also on other ecosystem components.

Detailed modeling of wildland fuels in space improves in our ability to assess changes in microclimate arising from fuel treatments, as well as to better understand the complexities of natural stands. A large number of spatially explicit light models have been developed (see Brunner 1998) but the majority of these focus on plant growth and thus do not consider fluctuations in solar radiation at temporal scales finer than a few weeks, as this tends to be the limit at which plant growth can be modeled (Brunner 1998). In fire and fuels applications such time scales are likely too coarse to capture much of the important dynamics, particularly with respect to dead fine fuel moisture, which exhibit significant sensitivity to solar radiation over short time periods (Nelson 2002). Current FUEL3-D research inquiries in this arena are directed at linking a ray tracing procedure to a dynamic fuel moisture model (Nelson 2002) in space. This will enable spatially and temporally explicit modeling of surface fuel moisture dynamics which can be used to quantitatively compare fuel treatments. Such detailed modeling will also likely also be of use in modeling shrub and grass growth response over time, a factor important to the effective duration of fuel treatments.

By quantitatively describing fuels at higher detail, FUEL3-D will promote an improved understanding of fire and fuels interactions. In conjunction with numerical fire behavior models such as FIRETEC or WFDS it will be possible to more precisely study transitions from surface to crown fire and develop species-specific thinning spacing guidelines. Analyses across scales will help to systematically identify conditions when greater complexity in modeling is required, and simpler conditions in which it is not. Correlative relationships observed through more intense numerical studies may be used to refine existing operational models. One advantage of FUEL3-D is its independence from any specific fire behavior model and its assumptions and limitations. At present the model is being designed to work with two numerical fire models, FIRETEC (Linn et al. 2002) and WFDS (Mell et al. 2005). As other models appear or as these models change FUEL3-D will be able to provide the needed inputs. The independence of the fuel model from particular fire behavior models provides flexibility and facilitates comparisons between models.

Finally, modeling fuel-fire interactions at fine scales will aid in a tighter coupling between fire behavior and fire effects. Most fire effects calculations are carried out as point calculations, where fuel consumption at a point or mortality of an individual tree are considered (Reinhardt et al. 2001). At present it is difficult to rectify the homogeneous stand-based fire behavior calculations from operational fire behavior models with point level fire effects predictions. Incorporation of finer detail in representation of fuels with FUEL3-D, and detailed spatially explicit fire behavior models will provide a basis for linkages between fire behavior, fuels and fire effects than has been possible before. This will improve our ability to define burn window prescriptions and anticipate the consequences of treatments or wildfire.

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FuelCalc: A Method for Estimating Fuel Characteristics

Elizabeth Reinhardt[1], Duncan Lutes[2], and Joe Scott[2]

***Abstract**—This paper describes the FuelCalc computer program. FuelCalc is a tool to compute surface and canopy fuel loads and characteristics from inventory data, to support fuel treatment decisions by simulating effects of a wide range of silvicultural treatments on surface fuels and canopy fuels, and to provide linkages to stand visualization, fire behavior and fire effects programs that rely on estimates of fuel loads and qualities.*

Canopy fuel characteristics, including available fuel, canopy bulk density, canopy base height and canopy cover are estimated from a list of trees.

***Key words**: canopy bulk density, canopy base height, wildland fuel, crown fire, fire behavior, biomass, stand table*

Introduction

Fuel treatment is mandated by the need to protect communities and municipal watersheds and manage ecosystems. Analysis to support fuel treatment decisions is required by the National Environmental Policy Act of 1969. In order to use the best available fire science in comparing fuel treatment alternatives, managers need access to high-quality fuel information, as well as the impact of fuel treatment alternatives on wildland fuels, fire behavior, fire effects, and fuel hazard. The most fundamental fuels information is, however, surprisingly hard to come by. We receive frequent requests for help from fuels managers who want to know simply: how can inventory data be converted to fuel quantities and qualities? Surface fuel loads, fire behavior fuel models, and canopy fuel characteristics are needed to model fire behavior, fire effects, smoke production, and to analyze fuel treatment alternatives. Managers need the ability to determine how these fuel quantities and qualities will change when treatments are applied to stands.

Site-specific, inventory-based data greatly strengthens the scientific foundation of fuel treatment decisions. Currently, although a variety of fuel analysis tools exist, it is quite daunting to perform these analyses with raw inventory data. There is a need for a simple, user-friendly, nationally applicable fuel analysis tool that accepts inventory data, allows users to simulate effects of silvicultural treatments on surface and canopy fuels, and provides linkages to other software for further analysis of fire behavior and fire effects in these fuels.

The FuelCalc computer program is a tool to meet these information needs. This tool, currently under development with support from the Joint Fire

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Science Program and the USDA Forest Service Rocky Mountain Research Station, will support fuel management decision-making directly and also provide input to a number of other analysis tools. This paper describes the sampling methods supported by FuelCalc, and the calculation procedures it uses to convert inventory data to estimates of fuel characteristics. It describes linkages and prescription development support provided by FuelCalc. Parts of FuelCalc, for example the canopy fuel calculations, are currently available in draft form, others are still in the design phase.

Fuel Strata in FuelCalc

Ground Fuels

Duff load information is critical in smoke management, soil heating, carbon balance, and site productivity applications. FuelCalc will include a method for estimating duff load based on a measurement of duff depth. Duff depth is multiplied by duff bulk density to estimate duff load. Duff bulk density can be entered or default values used based on cover type.

Surface Fuels

Surface fuel inventory may take a number of forms. FuelCalc will provide estimates from data collected using Brown's (1974) planar intercept method, Burgan and Rothermel's (1984) fuel sampling procedures, and Hardy's (1996) slash pile inventory method, as well as direct entry of fuel loads as estimated from photo-guides or other data sources. Crosswalks will be provided to standard fire behavior fuel models, and a first-cut custom fire behavior fuel model developed.

Planar intercept — Brown (1974) developed procedures for sampling down woody fuels by counting intercepts across a sampling plane by particles of different size classes. This is a well established method of inventorying woody fuels; FuelCalc contains procedures to convert this data to estimates of fuel loading.

Burgan and Rothermel — Burgan and Rothermel (1984) published a simple, effective method of inventorying surface fuel. The method relies on the relationship between fuel depth, load and bulk density. Field inventory requires estimates of depth and cover by life form, and the assignment of bulk density by comparison with photos. These inventory methods are supported in FuelCalc.

Hardy slash pile inventory — Hardy (1996) published guidelines for estimating biomass contained in slash piles. FuelCalc allows entry of pile shape and dimension, packing ratio and wood density, and uses these guidelines to estimate slash biomass.

Linkages to fire behavior fuel models — FuelCalc will provide a "best guess" standard fire behavior model (Scott and Burgan 2005) that seems to represent the sampled fuels.

Creation of custom fire behavior fuel models — FuelCalc will also provide a first cut custom fire behavior fuel model suitable for testing with BehavePlus (Andrews and Bevins 2003) or Nexus (Scott 1999).

Canopy Fuels

Van Wagner (1977) proposed a theoretical model suggesting that crown fire initiation is dependent on surface fire intensity and canopy base height, while sustained crown fire spread is dependent on crown fire rate of spread and canopy bulk density. His work has been further developed by Alexander (1988), Agee (1996), Scott and Reinhardt (2001), and Van Wagner (1993) and is incorporated in the Canadian Fire Behavior Prediction System (Forestry Canada 1992), FARSITE (Finney 1998), and NEXUS (Scott 1999).

Fire managers need estimates of canopy base height and canopy bulk density to use these fire models. The LANDFIRE program (Rollins, in prep.) has committed to mapping these variables at a 30 meter resolution for the continental U.S. In addition, land managers have a growing concern that crown fire activity may be increasing in some forest types due, in part, to fire suppression and resultant changes in stand structure. Assessing these changes in stand structure requires defining and consistently evaluating canopy fuel characteristics.

A rich body of literature exists quantifying tree crown and forest canopy characteristics for purposes other than fuel characterization. A number of studies exist that predict foliar and branch biomass from tree dimensions, typically diameter, sometimes in combination with height, crown ratio or sapwood thickness. Brown (1978) provides predictive equations for the common conifer tree species of the Inland West; Snell and Brown (1980), provide similar methods for Pacific Northwest conifers. A large number of allometric equations of this type from many research studies are summarized in the computer software BIOPAK (Means and others 1994). These equations, together with a list of trees representing a stand, may be used to estimate total foliar biomass, as well as biomass of branchwood of various sizes.

Canopy bulk density is the weight of available canopy fuel per unit volume of canopy space. It is a bulk property of the stand, not an individual tree. Estimates of total canopy biomass can be divided by canopy volume to estimate canopy bulk density. This method carries the implicit assumption that canopy biomass is distributed uniformly within the stand canopy. This assumption is unlikely to be true even in stands with very simple structures; multi-storied stands are likely even more poorly represented by this procedure.

Even canopy base height, a simple characteristic to measure on a single tree, is not well defined or easy to estimate for a stand. Neither the lowest crown base height in a stand nor the average crown base height is likely to be representative of the stand as a whole. In terms of its consequences to crown fire initiation, canopy base height can be defined as the lowest height above the ground at which there is sufficient canopy fuel to propagate fire vertically through the canopy. Using this definition, ladder fuels such as lichen, moss and dead branches can be incorporated. Sando and Wick (1972) suggested describing the canopy fuels by plotting the vertical distribution of available canopy fuel in thin (1-foot) vertical layers (figure 1). Canopy base height can then be computed as the height above the ground at which some critical bulk density is reached. Their method could also be used to define effective canopy bulk density. Scott and Reinhardt (2001) used the Sando and Wick approach in combination with Brown's (1978) equations to estimate canopy base height and canopy bulk density. Canopy base height was defined as the lowest height above which at least 100 lbs/acre/vertical foot of available canopy fuels was present. Canopy bulk density was defined as the maximum of a 15-foot deep running mean of canopy bulk density for one-foot deep vertical layers. This method has been incorporated into the Fire and Fuels

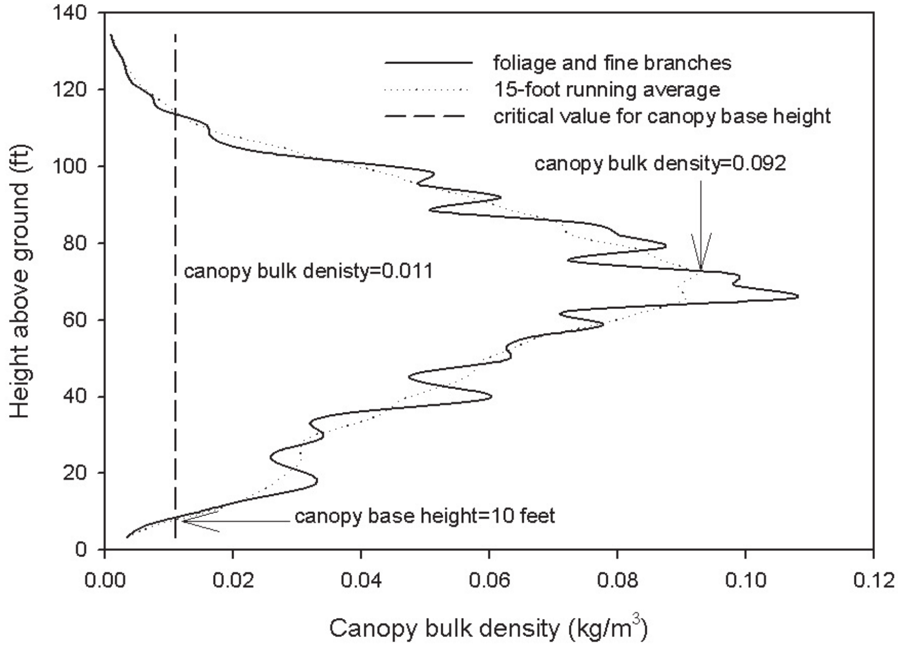

Figure 1—Vertical distribution of available canopy fuel as computed from a tree list using FuelCalc methods. Canopy bulk density is the maximum of the running mean. Canopy base height is the lowest point at which the running mean exceeds 0.012 kg/m^3, while stand height is the highest such point.

Extension to the Forest Vegetation Simulator (FFE-FVS, Reinhardt and Crookston 2003) and was validated by destructive sampling of forest canopies in five interior west conifer stands (Reinhardt and others, in prep.).

In FuelCalc we use this approach for computing canopy base height and canopy bulk density from a stand table or tree list. These methods have several advantages: 1. They do not require visual judgment calls or extensive interpretation that might result in inconsistent or subjective estimation, 2. They were developed with the underlying fire behavior models in mind, so the computed values are relevant in the context in which they will be used, 3. Because they are computed directly from a stand table or tree list they are derived using detailed information on stand structure, unlike methods based on image interpretation, 4. They can be performed quickly, using data sources that are widely available, so that values can easily be generated for thousands of stands.

Available canopy fuel load —Available canopy fuel load is assumed to be all the foliage and one-half of the 0-.25" branch material in the stand. We use Brown's (1978) equations for estimating the weight of foliage and small (0-1/4") branchwood for each tree from species and diameter. For some species no estimates of these components are available. In that case we use other published equations for total foliage biomass or crown biomass, if available, and crosswalk the proportions to Brown's equations. If no foliage or crown biomass equations of any kind are available, we crosswalk the species to a similar species that has published biomass relationships. These estimates are further adjusted to account for crown class (dominant, co-dominant, intermediate, suppressed) using adjustment factors developed in our canopy fuels field study (Gray and Reinhardt 2003). Trees less than 6 feet tall are excluded from the analysis, however, trees over 6 feet tall can contribute crown weight from branches less than 6 feet off the ground.

Canopy bulk density — Canopy base height is calculated by distributing the available crown fuel from each tree between its crown base and its top. The fuel is distributed vertically using regression equations developed from our destructively sampled data from 600 trees. These equations vary by species, but more biomass occurs higher in the crown. Fuel is summed in 1 foot height increments for all the trees in the stand. We smooth this profile with a 15-foot deep running mean, and define canopy bulk density as the maximum of this running mean.

Canopy base height —Canopy base height is computed in FuelCalc as the lowest point at which the running mean exceeds .012 kg/m^3 (33 lbs/acre/foot). This value, like Sando and Wick's 100 lbs/acre/foot, is arbitrary and not based on any kind of combustion physics, but it seems to perform well.

Stand height — Stand height is calculated in a way analogous to canopy base height, using the maximum height within the canopy at which canopy bulk density exceeds 0.012 kg/m^3.

Canopy cover — Canopy cover is estimated from the sum of the areas of individual tree crowns. Individual crown widths are computed from tree diameter (Moeur 1981). Following Crookston and Stage (1999), and assuming the crowns are randomly distributed within a stand, percent cover = $100(1-e^{-\text{totalcrownarea}/43560})$.

FuelCalc Linkages

FuelCalc is intended to make data management and analysis easy for managers by automating linkages to other software (figure 3).

FIREMON Database

For users who wish to store their data in a database, FuelCalc is linked to the FIREMON database (Lutes and others 2006). FIREMON provides a whole suite of statistical analysis tools. Similarly, FIREMON users will have the entire capability of FuelCalc available to them as an analysis tool, capable of reading data directly from the database.

SVS

The Stand Visualization System or SVS (McGaughey 1997) produces graphic representation of stands from tree list data (figure 2). These graphics are very helpful both for managers and even more importantly, for the public in assessing thinning treatments. FuelCalc will format data for use with SVS.

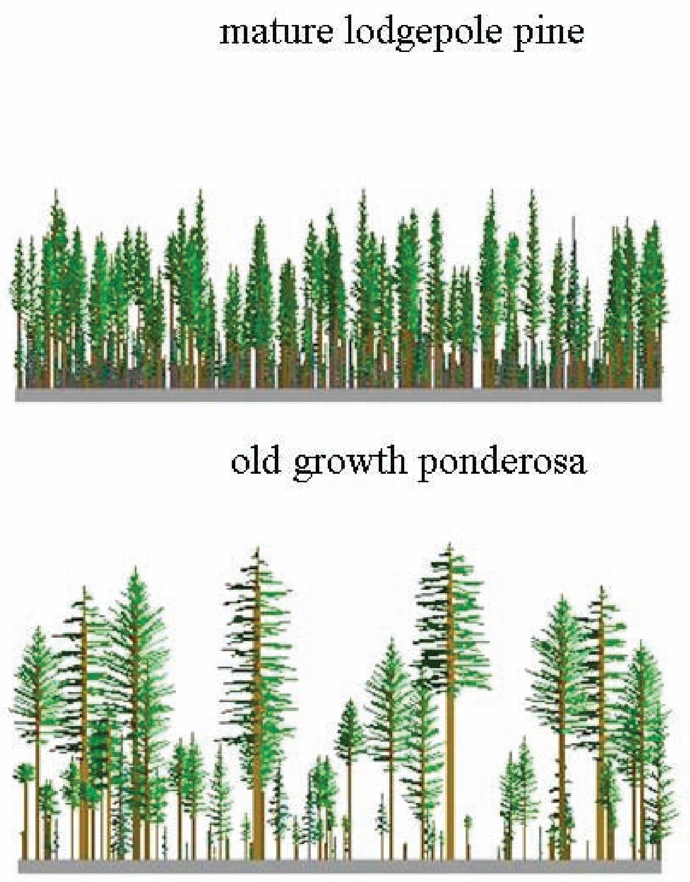

Figure 2—Examples of SVS (McGaughey, 1997) outputs.

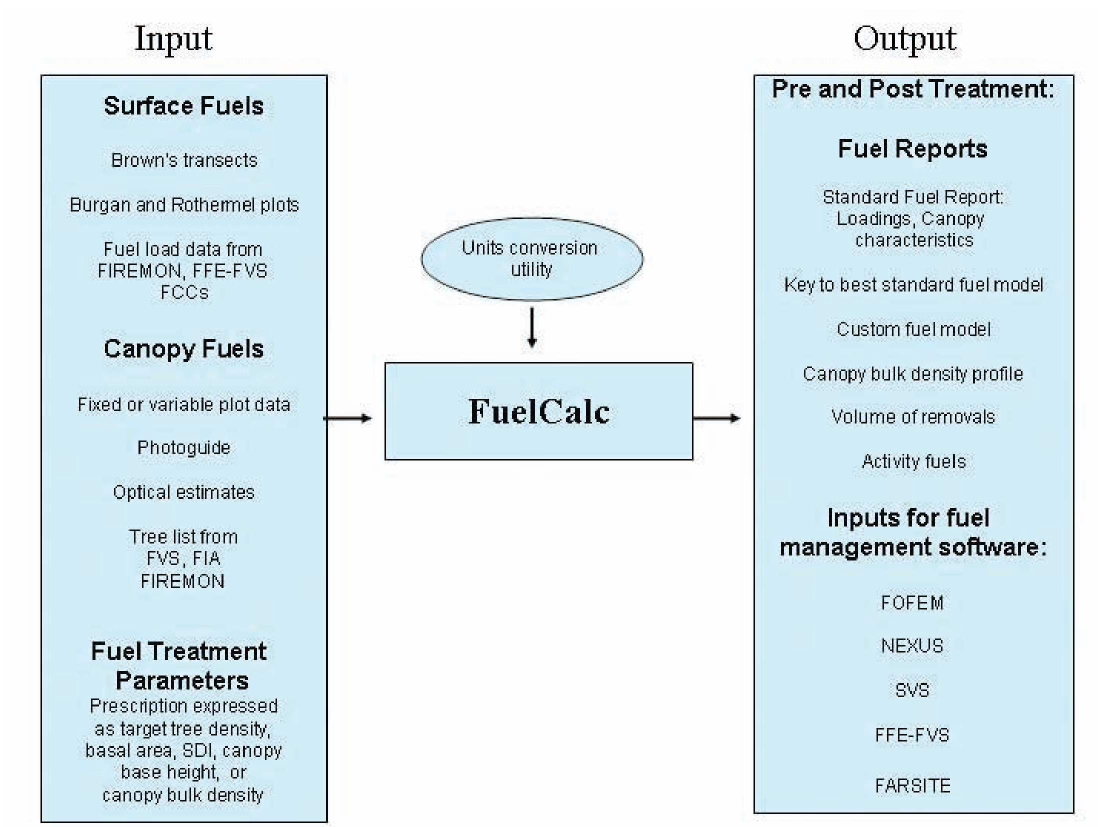

Figure 3—FuelCalc linkages.

FOFEM

FOFEM: a First Order Fire Effects Model (Reinhardt and others 1997, Reinhardt 2003) predicts tree mortality, fuel consumption, soil heating and smoke production from prescribed fire and wildfire. FOFEM requires as input exactly the kind of data that FuelCalc manages. FOFEM is widely used for NEPA documentation as well as smoke regulation. FOFEM will be fully integrated with FuelCalc so that as fuel treatment alternatives are developed within FuelCalc, FOFEM is invoked to assess impacts of those treatments on expected fire effects.

Nexus

Nexus (Scott 1999) is a fire behavior prediction system as well as a crown fire hazard assessment tool. It computes torching and crowning indices (Scott and Reinhardt 2001), as well as the full suite of fire behavior outputs including rate of spread, fireline intensity, and reaction intensity. Torching and crowning indices are windspeeds at which torching and active crowning can be expected to occur in a given fuel complex. Lower values indicate fuels that are more prone to crown fire behavior, i.e., crown fire can be expected at lower windspeeds. Torching and crowning indices vary as canopy and surface fuels are altered, thus they are useful indicators of crown fire hazard and of fuel treatment success. Nexus, like FOFEM, will be fully integrated with FuelCalc, so that as fuel treatment alternatives are developed in FuelCalc, expected changes in fire behavior and crown fire hazard can be assessed.

FFE-FVS

FuelCalc will convert data into files suitable for use with the Fire and Fuels Extension to the Forest Vegetation Simulator: FFE-FVS (Reinhardt and Crookston 2003). FFE-FVS can then be used to simulate treatment effects on fuels, potential fire behavior and stand structure over time.

National Volume Estimator Library

When thinning treatments are simulated, FuelCalc will use the National Volume Estimator Library of equations maintained by the USDA Forest Service Forest Management Service Center (USDA Forest Service 1993) in order to estimate the amount of potentially merchantable material that may be generated by thinning treatments.

FuelCalc Features

Prescription Design and Assessment

FuelCalc will provide analytical tools for prescription development. A user will be allowed to specify criteria such as: thin from below to a residual canopy bulk density of 0.05 kg/m^3, or thin from below to a residual basal area of 100 sq ft/acre, and FuelCalc will identify the number, volume, and characteristics of trees to be removed, as well as compute the activity fuels that would be generated by such a thinning. This analysis will combine the work of the JFSP-funded Canopy Fuels Study (Reinhardt and others 1999) with earlier work by Brown and Johnston (1976), and the National Volume Estimator Library (U.S. Forest Service 1993).

Batch Mode for Linking with GIS

FuelCalc is designed as a stand level tool, however, a batch mode will be provided to link with GIS and landscape level applications. We have successfully used this approach in developing FOFEM and Nexus. The LANDFIRE program has been using the batch FuelCalc program to process data from 1000s of plots.

Library of Code for Incorporation in Other Software

FuelCalc code will be provided on request to other software developers, hopefully resulting in more consistent use of inventory data across agencies and for a variety of applications.

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Accuracy and Precision of Two Indirect Methods for Estimating Canopy Fuels

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***Abstract**—We compared the accuracy and precision of digital hemispherical photography and the LI-COR LAI-2000 plant canopy analyzer as predictors of canopy fuels. We collected data on 12 plots in western Montana under a variety of lighting and sky conditions, and used a variety of processing methods to compute estimates. Repeated measurements from each method displayed considerable variability, but hemispherical photography proved to be the more precise method. To evaluate the accuracy of the different methods, we correlated measurements with allometrically derived estimates of canopy bulk density and available canopy fuel. Measurements from both methods were more highly correlated with available canopy fuel than canopy bulk density. Hemispherical photography emerged as the superior methodology, displaying greater precision and accuracy, at least when measurements must be collected under sub-par lighting conditions.*

In order to assess the potential risk of crown fires, accurate estimates of canopy fuel loads are needed. Direct met hods for measuring these loads are often difficult and time consuming, involving destructive sampling of the forest canopy or, alternatively, detailed allometric measurements on individual trees. As a result, indirect methods are being used increasingly to exploit the relationship between the amount of biomass in the forest canopy and the amount of light that gets transmitted to the forest floor. By measuring the relative amount of light reaching the forest floor, canopy fuels can be estimated indirectly.

This paper examines two indirect methods for measuring canopy fuels, the LI-COR LAI-2000 and hemispherical photography. Both of these methods have been used extensively to measure leaf area index (LAI), and are much less time consuming than direct methods (see Jonckheere and others 2004, or Chen and others 1997, for reviews of different methods for estimating LAI). Defined as the one sided leaf area per unit ground area, LAI is used frequently as a measure of canopy structure, and LAI has also been correlated with important metrics of canopy fuels loads, for example canopy bulk density (Keane and others, 2005). Thus these indirect methods could potentially provide an efficient method for estimating canopy fuel loads.

However, because these indirect methods rely on light transmittance, the resulting estimates can be highly sensitive to the ambient lighting conditions. Ideally measurements should be taken only at dawn or dusk with the sun below the horizon. Less ideally, data can also be collected under uniformly cloudy skies. In the former case, data collection is limited to only a few hours each day, while in the latter, data collection hinges on weather conditions. In practice these constraints may be too prohibitive, greatly limiting the time available for data collection. As a result they are often disregarded, and data are collected under a wide variety of lighting and sky conditions.

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In this paper, we evaluate the accuracy and precision of these two indirect methods with measurements taken under a variety of less than ideal lighting conditions. Using repeated measurements from 12 sites, we evaluate the precision of the estimates obtained using each method, and then compare these estimates with two allometrically derived metrics of canopy fuel loads: canopy bulk density (CBD) and available canopy fuel (ACF).

Background and Theory

Hemispherical photography and the LAI-2000 present different ways to measure the *gap fraction* in a stand: the proportion of sky visible under the canopy. With digital hemispherical photography, a digital camera with a fish eye lens is used to take a photograph of the canopy from which the gap fraction is computed. Usually this is accomplished by converting the color photograph to a black and white image: a threshold is chosen and all pixels darker than the threshold are declared to be not-sky and painted black, while all those brighter than the threshold are declared sky and painted white. The gap fraction is then equivalent to the proportion of white pixels in the image. Hemispherical photography requires little specialized equipment, simply a tripod, a digital camera, a fish eye lens, and software for processing the images.

The LAI-2000, on the other hand, is a specially produced piece of equipment for measuring LAI (LI-COR 1992). It consists of a light sensor mounted on a wand that is attached to an electronic control box. To compute gap fractions, the LAI-2000 needs to take two measurements of light intensity with the light sensor. The first measurement is taken above the forest canopy under open sky (usually in a clearing) while the second is taken below the canopy. The gap fraction is then computed by taking the ratio of these two measurements. Both measurements must be taken with the light sensor leveled and facing the same compass direction.

There is extensive theory detailing the relationship between gap fractions, leaf area index, and other canopy structure statistics (Welles and Norman 1991). Briefly, in an idealized homogenous full cover forest stand with small, randomly distributed foliage, the Beer Lambert law can be used to compute leaf are index, L, from gap fraction measurements as

$$L = 2\int_{0}^{\pi/2} -\ln(G(\theta))\cos\theta\sin\theta d\theta. \qquad (1)$$

Here θ denotes zenith angle and $G(\theta)$ is the gap fraction as a function of the zenith angle. In practice, this integral is usually approximated by dividing the continuous range of zenith angles $(0,\frac{\pi}{2})$ into a number of concentric rings or sectors. The gap fraction is measured at specific zenith angles (or over a range of zenith angles) and then L is given by a weighted sum,

$$L = 2\sum_{i=1}^{n} -\ln(G(\theta_i))W_i, \qquad (2)$$

Where n is the number of zenith angles (or number of rings) used, and W_i is the weighting term. The light sensor on the LAI-2000 has 5 rings centered at zenith angles of 7, 23, 38, 53, and 68 degrees. With hemispherical photography the number of rings and their locations can be controlled by the experimenter.

The LAI estimates derived from Hemi-photos and the LAI-2000 are very sensitive to lighting conditions. Both methods are best used under certain restricted light conditions: before sunrise, after sunset, or, less preferably, under uniformly cloudy skies (LI-COR 1992; Pepper 1998; Frazer 2001). Direct sunlight in a hemispherical photograph often leads to lens flare, and brightly lit foliage can be mistakenly classified as sky when hemispherical photographs are converted to black and white images for analysis. Similarly direct sunlight can lower resulting estimates from the LAI-2000 by up to 40% because of sunflects (Welles and Norman 1991). In practice appropriate lighting conditions can be difficult to obtain, greatly limiting the time available for data collection. As a result, these constraints are often neglected, or less data is collected. In this study, we examine how collecting data under sub-optimal lighting conditions affects the precision and accuracy of the measurements obtained.

Materials and Methods

Study Area and Sampling Methodology

The study area, located in Lolo National Forest in western Montana, consisted of 11 sample units, each 13m in radius. Each sample unit was either homogenously Douglas-fir (*Pseudotseuga menziessi*) or homogenously ponderosa pine (*Pinus ponderosa*). The tree densities varied substantially between plots (table 1). Nine of the plots were on south aspects, and 2 were on north aspects (plot codes DF-N and PP-N). Two of the Douglas-fir plots were open grown (DF-O-1 and DF-O-1) and located several miles from the others, in an area with thinner soil and higher winds.

Height, diameter and crown ratio measurements were collected on each tree in the study units, and then these tree lists were used to compute stand level canopy fuel load and bulk density, using methods described in Reinhardt and others (this proceedings).

Table 1—Fuel characteristics of the plots used in the study. Plots beginning with DF are homogenously Douglas fir, whereas those beginning with PP are homogenously ponderosa pine. All plots are circular with a radius of 13 m.

Plots					
Index	Plot Code	Canopy Bulk Density (Kg/m^3)	Available Canopy Fuel (Tons/Acre)	Canopy Cover (%)	Tree per acre
1	DF-2	0.0801	5.587	48.68	137
2	DF-3	0.1290	5.444	46.32	107
3	DF-4	0.2752	9.567	68.40	244
4	DF-N	0.0633	3.718	35.13	84
5	DF-0-1	0.0122	0.891	9.27	8
6	DF-0-2	0.0703	3.518	33.90	84
7	PP-1	0.0895	2.239	37.18	274
8	PP-2	0.0922	2.533	39.21	305
9	PP-3	0.0244	0.508	9.73	53
10	PP-4	0.1082	2.750	42.06	290
11	PP-N	0.0848	4.127	42.87	198

Hemispherical photographs and readings with the LI-COR LAI-2000 were collected in early September 2004. Data were collected under a variety of lighting and sky conditions, and in total measurements were taken 12 times with each instrument on each sample area.

A Nikon Coolpix 9000 digital camera with a fisheye lens was used for taking hemispherical photographs. The camera was attached to a leveled tripod and aligned so that the camera body pointed north. On each visit to a plot, two photographs were taken sequentially: one with proper exposure as determined by the camera's automatic metering and one underexposed by two f-stops. All photographs were taken using the highest resolution setting.

Two LICOR LAI-2000 units were used to obtain the above and below canopy measurements. The first unit was set up in a centrally located clearing, leveled, aligned to the North, and automatically logged above canopy readings every 30 seconds. The other unit was used to record the below canopy readings, and on each visit to a plot two below-canopy readings were taken immediately after the hemispherical photographs. The wand on the below canopy unit was leveled and aligned to the north for each measurement. Each LAI-2000 unit used a 90° view cap.

Data Processing

To compute gap fractions for the LAI-2000, we individually matched each below canopy reading with the above canopy reading that was closest in time, and computed gap fractions at each of the five zenith angles. Computing gap fractions for the hemispherical photographs was more complicated, as the color photographs first had to be converted to black and white images. Usually this is accomplished by choosing a threshold and coloring all pixels darker than the threshold black (vegetation) and all others white (sky). However, under uneven lighting conditions this approach can result in substantial misclassifications because foliage near the sun appears brighter than the sky far from the sun.

Instead, we used a two-stage supervised clustering algorithm to convert the color photographs to black and white images. The algorithm is an example of a commonly used iso-clustering algorithm from the image processing literature (Richards 1996), and was implemented in ARC-GIS. Briefly, the algorithm uses an automated procedure to assign each pixel in the image to one of a user-specified number of bins, based on the color and brightness attributes of the pixels in the image. In the first stage of processing, the photograph was divided into ten bins and the user was then prompted to classify each bin as not-sky (black), sky (white), or unknown (red). Often a single bin contained both vegetation and sky, and these bins were classified as unknown in the first stage. Any pixels classified as unknown during the first stage were then further subdivided into seven bins for a second stage of classification. The result was a black and white image with generally more fine detail than was obtainable using the traditional single threshold approach.

The resulting black and white images were then input into the commercial software HemiView for analysis. HemiView divides each image into a user-specified number of concentric circles (rings) of equal width, corresponding to different zenith angles, and then computes the average gap fraction in each ring. To facilitate comparison with estimates from the LAI-2000, five rings were used, centered at zenith angles of 9, 27, 45, 63, and 81 degrees. Note that the zenith angles from the two techniques are different, since the rings in the LAI-2000 are of unequal width.

There are potentially many ways to combine the individual gap fractions at each zenith angle into estimates of the overall LAI or fuel on a plot. The standard method is to compute LAI using all five zenith rings by taking a weighted sum of the logarithm of the gap fractions, i.e. equation 2. Not all rings need to be included in the sum however, and we also computed LAI values using different subsets of the zenith rings.

Moreover, it may be that the raw un-weighted gap fractions prove to be better indicators of canopy fuel loads. In this case the average gap fraction, $\bar{G}$, will be a useful statistic:

$$\bar{G} = \frac{1}{n}\sum_{i=1}^{n} G(\theta_i). \qquad (3)$$

As with the LAI based statistics, this sum can be computed over different subsets of the zenith rings. In the following analysis, we utilized several different sets of zenith rings and computed predictions using both the raw gap fractions and the log transformed and weighted LAI as the predictive statistic (table 2).

Results

Comparing the Different Methods

We computed the mean, variance, and coefficient of variation (CV), for each method on each plot (table 3). The mean variance and CV per plot are both consistently larger for the LAI-2000 estimates than for the hemi-photo estimates. There is also a tendency for the CV and variance to increase as the number of rings used in the analysis is reduced. Note, however, that the estimates derived using only the 3rd ring do not conform to this pattern, suggesting that the number of rings is less important than the zenith angles of the rings used. Estimates derived using the smaller zenith angles exhibit more variation than do estimates derived from the larger angles.

Table 2—Factors in the analysis. Gap fractions were obtained with either the Licor unit or hemispherical photographs. Either the mean gap fraction or the log transformed and weighted leaf area index was used to derive predictions. The different analysis schemes used between and five zenith rings to derive predictions.

Methods	
Licor	LAI-2000 plant canopy analyzer
Hemi	Hemispherical photography
Statistics	
GF	Mean gap fraction (unweighted)
LAI	Leaf area index (weighted mean of the logarithm of individual gap fractions)
Analysis Scheme	
1	Only third zenith ring
2	Top two zenith rings
3	Top three zenith rings
5	All five zenith rings

Table 3—Summary statistics of the LAI estimates produced using different methods. The average variance and CV per plot represent the variance (CV) in measurements on each plot averaged across all the plots. Similarly the variance (CV) across plots denotes the variance (CV) in the mean value of the measurements for each plot. Note that these are the results using the LAI statistic.

Method	Mean	Average Variance Per Plot	Average CV Per Plot	Variance Across Plots	CV Across Plots
LAI-2000					
LAI-5	1.04	0.18	0.46	0.16	0.38
LAI-3	1.13	0.32	0.71	0.37	0.54
LAI-2	0.90	0.33	1.05	0.52	0.80
LAI-1	1.33	0.56	0.70	0.42	0.49
Hemi					
LAI-5	1.80	0.04	0.09	0.33	0.32
LAI-3	1.69	0.09	0.15	0.52	0.43
LAI-2	1.55	0.13	0.19	0.88	0.61
LAI-1	1.82	0.08	0.14	0.33	0.32

For the hemi-photos, the variance and CV across plots is substantially larger than the average variance and CV per plot, suggesting that the method can consistently distinguish between some of the plots. However, the LAI-2000 readings have roughly similar variances between and across plots, and the CV across plots is actually smaller than the average CV per plot. The mean estimates of LAI from the LAI-2000 are consistently lower than those from the hemi-photos for all of the different ring choices. Also, the mean estimated LAI values from the hemi-photos decrease as the rings with larger zenith angles are removed from the analysis.

To examine the correlation between the LAI-2000 estimates and the hemi-photo estimates, we computed simple correlation coefficients for each pair of estimates (table 4). The correlation between the LAI-2000 and hemi-photo estimates increases as the rings with the larger zenith angles are excluded from the analysis. Measurements were most correlated when only the top two zenith rings were used.

Table 4—Correlation coefficients between the hemi-photo and Licor LAI values.

	Licor LAI-2000			
Hemi-Photo	LAI-5	LAI-3	LAI-2	LAI-1
LAI-5	0.561	0.618	0.673	0.429
LAI-3	0.602	0.659	0.667	0.499
LAI-2	0.594	0.683	0.717	0.496
LAI-1	0.560	0.570	0.543	0.459

Relationship with Allometric Data

For all processing methods, we computed regressions using both available canopy fuel (ACF) and canopy bulk density (CBD) as computed from the stand data as response variables. We tested three different regression models. The simplest, the reduced model, used only the measured LAI or GF statistic as a predictor variable, but the other two regressions incorporated additional predictor variables. The second regression model introduced tree type (Douglas fir or Ponderosa pine) into the reduced model as a categorical predictor variable, including an interaction term. This approach is justified due to the homogenous nature of the stands in the study and the common use of species specific clumping factors for modifying LAI estimates (White and others 1998). Finally the third regression model further added canopy base height as an additional predictor variable. Canopy base height is defined as the average height within a stand from the ground to the canopy bottom. While more difficult to assess than tree type, canopy base height can be measured or estimated relatively easily.

To simply the presentation, we use R^2 values to measure goodness of fit (figure 1). For each of the two instruments there were two possible statistics (GF or LAI), four analysis schemes, two response variables, and three types of regression models, for a total of 2x2x4x2x3 = 96 different regression models.

Several clear patterns emerge from figure 1. The reduced regression model, using a single predictor, performs uniformly poorly for both instruments and both predictor variables. The third regression model, which includes canopy base height, performs substantially better than the other two, especially for hemispherical photography with CBD as the response variable. For all of the

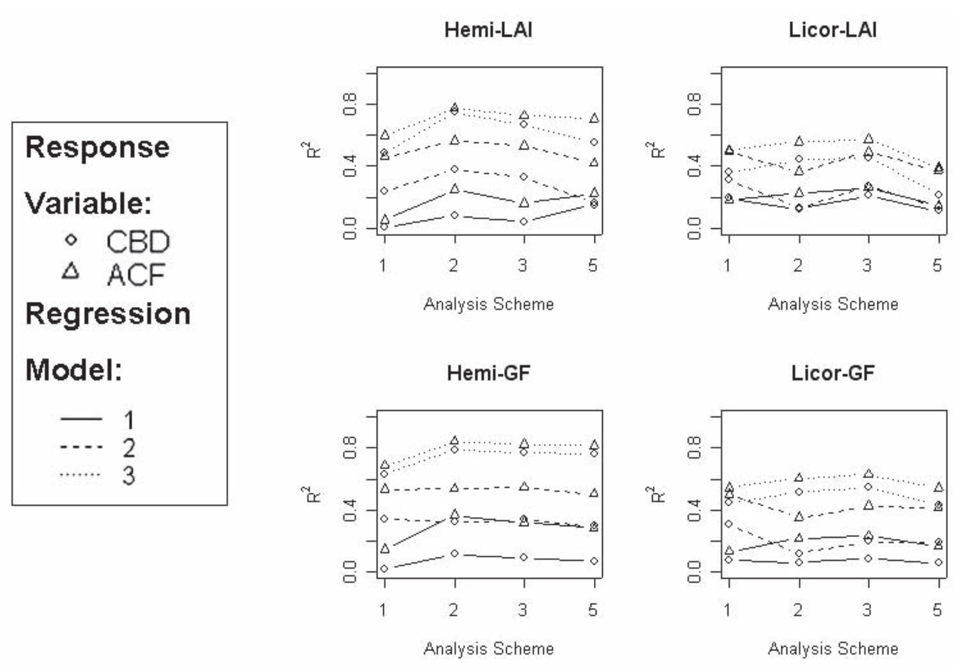

Figure 1—R^2 values from the different regressions. The x-axis shows the number of zenith rings used to derive predictions. Regression model 1 (solid lines) is the reduced model, model 2 (dashed lines) includes tree type as a predictor, and model 3 (dotted lines) also includes canopy base height. Results are shown with available canopy fuel (ACF) or canopy bulk density (CBD) as the response variable.

regression models, the fit was better using ACF as the response variable than it was with CBD as the response variable. The LAI-2000 estimates derived using only the third ring (analysis scheme 1), as well as those derived using the top 3 rings (analysis scheme 3), produced the best fits for both CBD and ACF. Conversely, the hemi-photo estimates derived using the top two rings consistently had the largest R^2 values, although only marginally larger than those derived using the top 3 rings. For the hemi-photos, correlations generally increase as the zenith angles increase, but for the LAI-2000 correlations appear to peak around the third zenith angle. Overall, there appears to be little overall difference in performance between the estimates produced using LAI and those produced using average GF.

With the simplest regression model, the hemi-photos and LAI-2000 both performed similarly. In the more complex regression models, however, the hemi-photo results were clearly dominant, with consistently larger R^2 values than the corresponding LAI-2000 based estimates. This suggests that hemi-photo based estimates of CBD and ACF are more accurate.

Discussion and Conclusions

As is clear from table 2, the hemi-photo measurements are more precise than the LAI-2000 measurements, with substantially smaller variances and CVs on each plot. The hemi-photos also provided more accurate measures of canopy fuels, as indicated by the R^2 values from the regressions against CBD and ACF.

The number of rings used in the analysis had a somewhat significant impact on the accuracy of the different estimates (table 4). The tendency towards increased accuracy with reduced zenith angles may be due to the relatively small size (13m radius) of the plots used. In any case, as the zenith angles used for analysis decreased, the CV of the measurements on each plot tended to increase. Taken together these results suggest that accuracy can be increased, at least on smaller plots, by only using the smaller zenith angles, but at the cost of decreasing the precision of the measurements.

The lower precision of the LAI-2000 estimates is not surprising: the LAI-2000 is not intended to derive estimates from individual measurements. Indeed, part of the attraction of using the LAI-2000 is the ease of taking repeated measurements on a single plot. Whereas repeated measures using hemi-photos require analyzing each photograph individually, the LAI-2000 can automatically combine repeated measures into a single estimate. Thus the lower precision of individual measurements is offset by the ease of repeating measurements. The large processing time needed to derive estimates from the hemi-photos, and the relative ease of incorporating multiple measurements into a single estimate using the LAI-2000, makes the LAI-2000 more competitive than the preceding analysis might suggest. Nonetheless, this analysis demonstrates that the hemi-photo method is preferable from the standpoint of both accuracy and precision. If the processing of the hemi-photos could be completely automated, the processing time would be more comparable for the two methods, and the hemi-photo methodology would be more clearly preferable.

Surprisingly the hemi-photos provided decent measures of canopy fuels despite the variety of less than ideal lighting and sky conditions under which the photographs were taken. In this study we used a very labor intensive processing methodology that allowed for more detailed black and white photographs even under poor lighting conditions such as direct sunlight. Apparently more labor intensive processing in the lab was able to compensate for less than ideal sampling conditions in the field. Hemispherical photography thus has the potential to reduce the labor, time, and environmental constraints in the field, in exchange for more time and labor spent in the lab.

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Mapping Fuels on the Okanogan and Wenatchee National Forests

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Abstract—*Resource managers need spatially explicit fuels data to manage fire hazard and evaluate the ecological effects of wildland fires and fuel treatments. For this study, fuels were mapped on the Okanogan and Wenatchee National Forests (OWNF) using a rule-based method and the Fuels Characteristic Classification System (FCCS). The FCCS classifies fuels based on their combustion properties, producing unique "fuel beds," each of which represents a distinct fire environment. Managers on the OWNF identified 187 fuel beds which were consolidated into 40 general fuel beds representing the major vegetation forms (forest vs. non-forest) and species groups. Fuel beds were assigned to each 25-m cell in the forest domain (27,353,425 cells) using decision rules based on a combination of spatial data layers. General fuel beds can then be subdivided into specific structural types using spatial data on canopy cover, quadratic mean diameter, and past disturbances (fires, insects, and management). This rule-based approach allows for the incorporation of more specific data if available or a more general classification if they are unavailable, and for reclassification when new data become available. Key uses of the fuels map include spatially explicit modeling of fire effects and assessment of spatial patterns of fire hazard under different management strategies.*

Introduction

Fuel mapping is a complex and often multi-disciplinary process, potentially involving remote sensing, ground-based validation, statistical modeling, and knowledge-based systems (Huff et al. 1995; Burgan et al. 1998; Keane et al. 2000, 2001; Rollins et al. 2004). There are strengths and weaknesses of each technique, and a combination of methods is often the best strategy (Keane et al. 2001). The scale and resolution of fuel mapping efforts depend both on objectives and availability of spatial data layers. For example, input layers for mechanistic fire behavior and effects models must have as high resolution (≤ 30 m) as possible (Keane and Finney 2003).

Because of the time and effort required for ground-based measurements and the intrinsic variability of fuel loads, even at fine scales, estimation of fuel loadings across broad extents must rely on indirect methods. For example, Ohmann and Gregory (2002) built stand-level models of vegetation, including fuel loads, from inventory plots, satellite imagery, and biophysical variables, and used nearest-neighbor imputation to assign them to unsampled plots (cells). Keane et al. (2000) used satellite imagery, terrain modeling, and simulation models to develop predictions of biophysical setting, vegetation cover, and structural stage, from which they assigned each cell a fire behavior fuel model (Anderson 1982). Both these efforts are *model-based* classifications.

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At broader scales, or where no ground data are available, fuel-mapping relies mainly on classifications of remotely sensed imagery and existing spatial data (for example, Burgan et al. 1998). *Knowledge-based* classifications (Schmoldt and Rauscher 1996) are often appropriate when there are multiple uncertainties associated with scaling predictive models (Rastetter et al. 1992, McKenzie et al. 1996). *Rule-based* classifications are knowledge-based methods that invoke a rule set: a collection of inferences that can be qualitative, or numerical, or both (Puccia and Levins 1985, Schmoldt and Rauscher 1996).

The choice between rule-based and model-based classifications involves trade-offs. Model-based methods provide quantitative estimates of variance and uncertainty whereas rule-based methods only provide qualitative estimates. A poor quantitative model is generally less useful than a qualitative model, (Puccia and Levins 1985, Schmoldt and Rauscher 1996, Schmoldt et al. 1999), so mapping efforts for which quantitative models perform poorly or cannot be validated are good candidates for rule-based methods.

Ecosystems are dynamic and fuel loadings change with succession, in response to climatic variability, or after disturbance. Quantitative fuel maps can become obsolete rather quickly. In order to keep fuel maps current so that they will retain their value for users, methods are needed to update fuel layers efficiently as landscapes change. An advantage to rule-based mapping is that new data layers can be incorporated efficiently because rules only need to be built for new attributes. In contrast, bringing updated data layers into model-based mapping requires entirely new models because relationships between response and predictor variables will change.

In this paper, we demonstrate the use of FCCS for fuel mapping on the Okanogan (ONF) and Wenatchee National Forests (WNF) at 25-m resolution. We focus on the process of assigning a unique *fuel bed* (Riccardi et al., in review) to each mapped cell in a spatial data layer and show how the classification scheme in FCCS, based on dominant vegetation, facilitates the use of existing GIS layers in developing classification rules and ongoing updates of fuel bed maps as new GIS layers become available. We briefly discuss how assigning actual fuel loads to cells can proceed. Finally, we discuss applications of FCCS-based fuel maps for both modeling and management.

Methods

Study Area

The Okanogan (690,400 ha.) and Wenatchee National Forests (890,000 ha.) are in north central Washington State extending from the crest of the Cascade Range eastward to savanna-steppe and agricultural lands. Near the crest topography is extremely rugged, with deep and steep-sided valleys. Climate is intermediate between the maritime climate west of the Cascade Crest and the continental climate east of the Rocky Mountains. The Okanogan highlands portion of the ONF lies further east and topography there differs from the western portion by having more moderate slopes and broad rounded summits. Conifer species dominate, notably subalpine fir (*Abies lasiocarpa*) and mountain hemlock (*Tsuga mertensiana*), at higher elevations and ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*) at lower elevations.

Spatial Data Layers

We used GIS layers developed from a variety of sources and archived by the ONF and WNF. We selected the best available (highest level of local manager confidence) spatial data layers for each forest so techniques and methods differed based on the layers chosen. ArcGIS 9.0 (ESRI 2005) was used for all GIS computations.

For the WNF we used a 25-m raster layer (R6) and a photo-interpreted polygon layer (WenVeg) of cover type. The R6 layer comprises 6 cover types from a direct classification of LANDSAT TM imagery and 9 forested cover types from an interpretation of the cover classes in terms of potential natural vegetation (Lillybridge et al. 1995). The WenVeg layer distinguishes 26 forest types, each of which has one or more structural or age classes associated with it. WenVeg polygons were classified from aerial photos, and range in size from less than 1 ha to 28,000 ha, but with only 18 polygons larger than 4,000 ha. Many polygons were validated by site visits or expert local knowledge of ecologists on individual forest districts. The R6 layer was converted to polygons, then overlain with the WenVeg layer. We created a new coverage of the combined polygons whose attribute table retained the attributes of the original layers.

For the ONF we used a 30-m resolution raster layer of modeled hierarchical potential vegetation consisting of 10 vegetation zones (VZ) subdivided into 42 plant association groups (PAG), and a 25-m resolution raster layer of 36 cover types classified from LANDSAT TM imagery (USU 1997). Forest managers on the ONF conducted an accuracy assessment of the USU LANDSAT TM imagery and reclassifications were done when necessary (K. Davis, personal communication, 2006). The 30-m resolution PAG layer was resampled to 25-m and the resampled PAG layer and the USU layer were overlain and combined to create a new raster layer of all possible combinations of PAG and USU cover types.

Fuel Bed Development

Forest managers from the ONF and WNF collaboratively designed 187 fuel beds with distinct species composition, stand structure, and disturbance histories. We aggregated these into 35 general fuel beds based on forest composition, within which one or more structural or age classes could be distinguished (for example, table 1). Additional spatial data on disturbance history, canopy cover, and stand structure can be used to distinguish the 187 specific fuel beds (see Discussion).

Table 1—Sub-categories of a generic fuel bed (Douglas-fir, moist grand fir) on the Okanogan and Wenatchee National Forests based on structure, age class, and disturbance.

Fuel bed ID	Age range (yrs)	Structure	Change agent
OW020	0-30	Created opening	Wildfire
OW021	30-60	Seedlings & saplings	Pre-commercial thin
OW022	30-60	Seedlings & saplings, high density & load.	None
OW023	60-90	Poles	Selection cut and burn
OW024	60-90	Poles	None
OW025	90-200	Multi-layer	Selection cut & burn
OW026	90-200	Multi-layer, high density & load.	None
OW027	Over 200	Layered mature, medium density & load.	None
OW028	Over 200	Layered mature, high density & load.	None
OW029	Over 200	Open parkland, low density & load.	None
OW030	Over 200	Open parkland, medium density & load.	None

We used 1,490 plots from the USFS Pacific Northwest Region Current Vegetation Survey (CVS) on ONF and WNF to determine if the designated fuel beds adequately represented the likely species combinations. Some species and species combinations were poorly represented by the original 35 general fuel beds, so we added 5 general fuel beds. A limiting factor of using available spatial data is that some species are difficult to map due to the resolution of the data layers. For example, the initial list included fuel beds dominated by both whitebark pine (*Pinus albicaulis*) and subalpine larch (*Larix lyallii*), but the spatial layers lumped these species into one high-elevation parkland classification, so we added a corresponding high-elevation parkland fuel bed.

Fuel Bed Assignment

We assigned a fuel bed to each 25-m cell in the forest layers using a rule-based approach that incorporated the GIS layers for each national forest. The overarching criterion for the WNF was that the fuel bed assignment first had to be consistent with the WenVeg layer, because this was the one in whose accuracy local managers had the most confidence. Because WenVeg does not distinguish species composition as finely as the general fuel beds, however, we used the R6 layer to narrow possibilities for dominant species. For each R6 cell within each WenVeg polygon, the most likely fuel bed was assigned. Figure 1 illustrates the logic for three distinct fuel bed assignments within

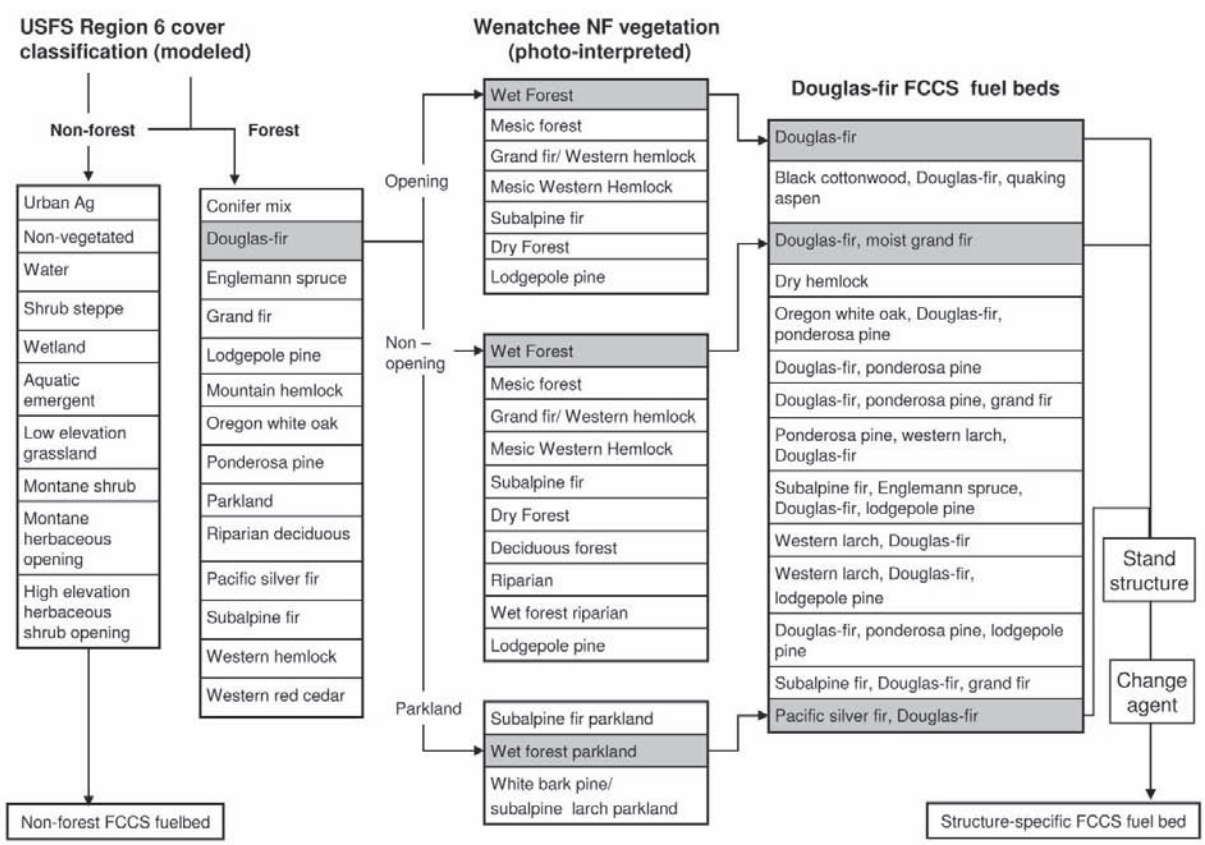

Figure 1—Example of logic for identifying a generic FCCS fuel bed for combinations of satellite-mapped vegetation and photo-interpreted vegetation on the Wenatchee National Forest.

the cover class “Douglas-fir” in the R6 layer, depending on the WenVeg polygon within which they fall. The LANDSAT-based cover type classification was the primary GIS layer used to assign fuel beds on the ONF because it was a measure of current vegetation for which an accuracy assessment was completed. If the cover type was not specific, it was further refined using the VZ, and if the cover type classification was common and coincided with many PAG, the PAG were also used to assign the most likely fuel bed. Figure 2 illustrates the logic for assigning fuel beds to the “Douglas-fir” LANDSAT-based cover type in the USU layer.

We used the CVS plots to validate the fuel bed assignments based on the remotely sensed data. The objective of this validation was to compare the frequency distribution of fuel beds represented in the spatial data layer with that of fuel beds represented by the CVS plots, not to match individual cells to individual plots. First we assigned a fuel bed to each of the CVS plots based on the relative tree species composition by basal area giving weight to the most dominant species and the presence of rare species. Each CVS plot is a cluster of five subplots in which trees were sampled in a 15.6 m radius circular plot (0.076 hectares). To compare fuel beds at a commensurate scale, only data from the center plot were used, which corresponded to one 25-m grid cell.

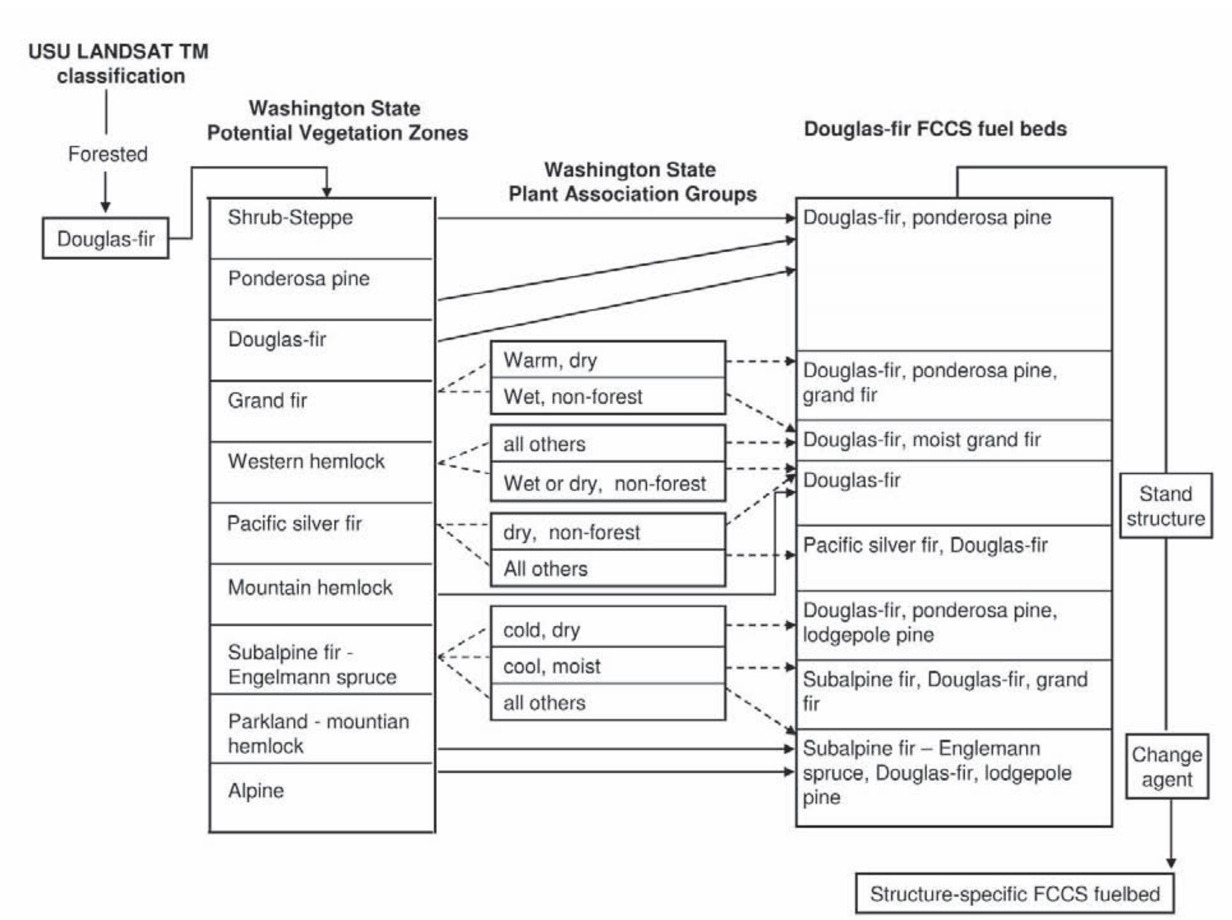

Figure 2—Example of logic for identifying a generic FCCS fuel bed for combinations of satellite-mapped vegetation and modeled potential vegetation on the Okanogan National Forest.

Results

The combination of 9 R6 modeled vegetation types and 6 LANDSAT-based cover types with 26 classes from the photo-interpreted WenVeg layer yielded 34 general fuel beds (figure 3) including 6 common (greater than 1,000,000 cells) and 5 rare (less than 10,000 cells) fuel beds (table 2). "Western hemlock, Pacific silver fir, mountain hemlock" was most prevalent, accounting for 14 percent of the mapped area (2,233,445 cells). The commonness reflects both the range of vegetation and the range of possible fuel bed choices. For example, fuel bed choices for the WNF included only two dominated by western hemlock and only one dominated by mountain hemlock, but five dominated by Douglas-fir. Five fuel beds with western larch or western white pine as a significant component were not mapped on the WNF due to the limited resolution of the original GIS layers. These species are problematic for the rule-based logic of assigning fuel beds on the WNF, because even when present, they rarely dominate stands or represent the climax species.

As would be expected, the rarest fuel beds reflect the species with more restricted ranges in the study area: Oregon white oak (*Quercus garryana*) and Engelmann spruce (*Picea Engelmannii*). The WNF map showed areas of greater homogeneity in the middle elevations on the west side of the forest where "Western hemlock, Pacific silver fir, mountain hemlock" and "Mountain hemlock, Pacific silver fir, subalpine fir" occur in large patches. In contrast, patterns in the lower elevations on the east side of the forest were more heterogeneous, a consequence of both more fuel bed options and a more patchy disturbance regime creating finer-scale spatial variability.

The combination of PAG and LANDSAT-based cover types yielded 36 fuel beds on the ONF (fig. 4)including 4 common (greater than 1,000,000 cells) and 6 rare (less than 10,000 cells) fuel beds (table 3). The most frequently occurring fuel bed was "Subalpine fir, Engelmann spruce, Douglas-fir, lodgepole pine" covering 16 percent of the area (1,776,623 cells). All fuel beds were mapped except the two Oregon white oak fuel beds because the area is beyond its range. The greater specificity of the LANDSAT-based cover type layer on the ONF better captured rare species such as Engelmann spruce, white bark pine, western larch, and western white pine. The greater frequency of these fuel beds reflects both the higher number of categories in the USU LANDSAT layer and the greater abundance of these species on the ONF. The pattern of fuel beds across the ONF domain distinguishes four general areas: (1) the western portion of the forest along the Cascade crest and west of the crest is dominated by the Mountain hemlock, silver fir, subalpine fir" fuel bed, (2) the north east is dominated my lodgepole pine fuel beds, (3) the south east is dominated by Douglas-fir and ponderosa pine fuel beds and (4) the Okanogan highlands is highly variable with the greatest fuel bed heterogeneity.

Validation

Validation of fuel beds on the WNF indicated a bias towards fuel beds composed of late seral species (for example, western hemlock, Pacific silver fir, mountain hemlock) and dry forest fuel beds were under-represented (for example, Douglas-fir, ponderosa pine, grand fir) (figure 5). This was not entirely unexpected as one of the spatial data layers was partially developed from modeled potential vegetation. To adjust for this bias, we revisited each classification rule, under the assumption that a systematic shift towards the early seral species in the R6 plant associations would correct the bias. However,

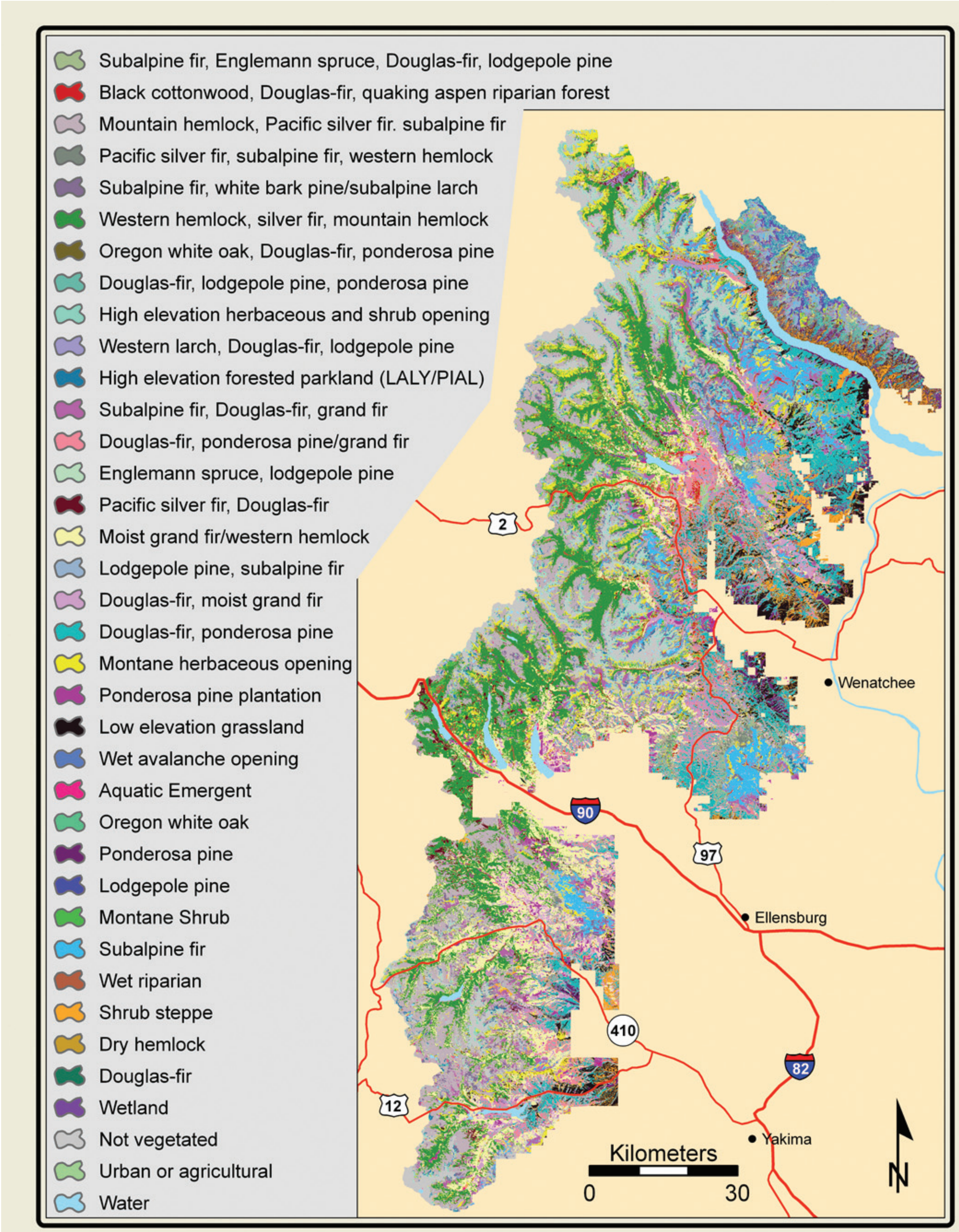

Figure 3—Fuel bed classification for the Wenatchee National Forest, Washington state, at 25-m resolution.

Table 2—Percentage area of the common (> 1,000,000 cells) and rarest (< 10,000 cells) fuel beds in the Wenatchee National Forest map.

Common fuel beds	Area (%)
Western hemlock, Pacific silver fir, mountain hemlock	13.84
Mountain hemlock, Pacific silver fir, subalpine fir	9.66
Douglas-fir, ponderosa pine	9.07
Moist grand fir, western hemlock	8.47
Non-vegetated	8.07
Montane herbaceous opening	7.10
Rare fuel beds	
Dry hemlock	0.038
Oregon white oak, Douglas-fir, ponderosa pine	0.032
Engelmann spruce, lodgepole pine	0.011
Wet avalanche opening	0.002
Oregon white oak	< 0.001

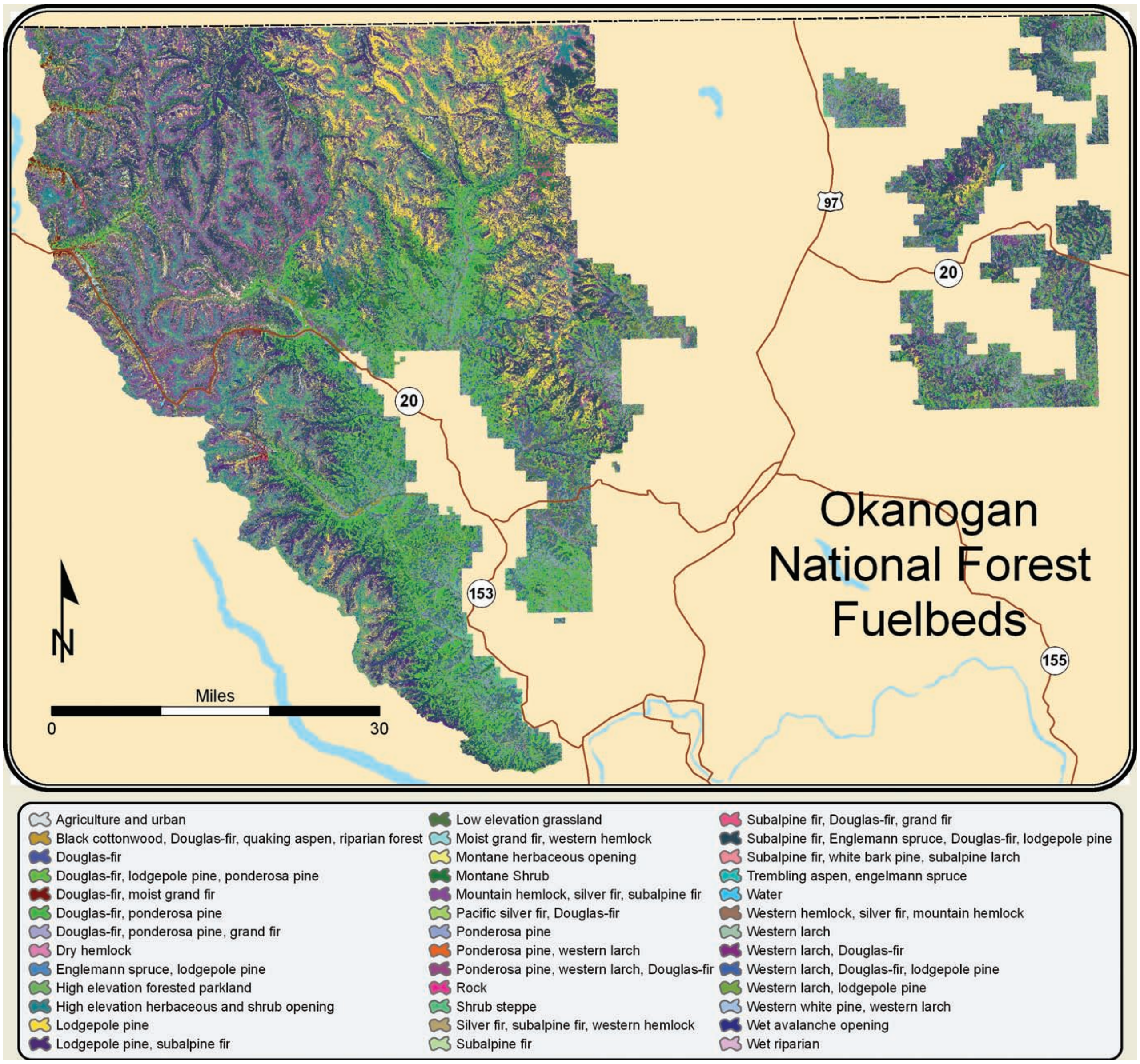

Figure 4—Fuel bed classification for the Okanogan National Forest, Washington state, at 25-m resolution.

Table 3—Percentage area of the most common (> 1,000,000) and rarest (< 10,000) fuel beds in the Okanogan National Forest map.

Common fuel beds	**Area %**
Subalpine fir, Engelmann spruce, Douglas-fir, lodgepole pine	15.84
Douglas-fir, ponderosa pine	14.29
Lodgepole pine	9.92
Lodgepole pine, subalpine fir	9.10
Rare fuel beds	
Low elevation grassland	0.079
Dry hemlock	0.054
Western larch	0.031
Western larch, lodgepole pine	0.024
Wet riparian	0.016
Ponderosa pine, western larch	0.006

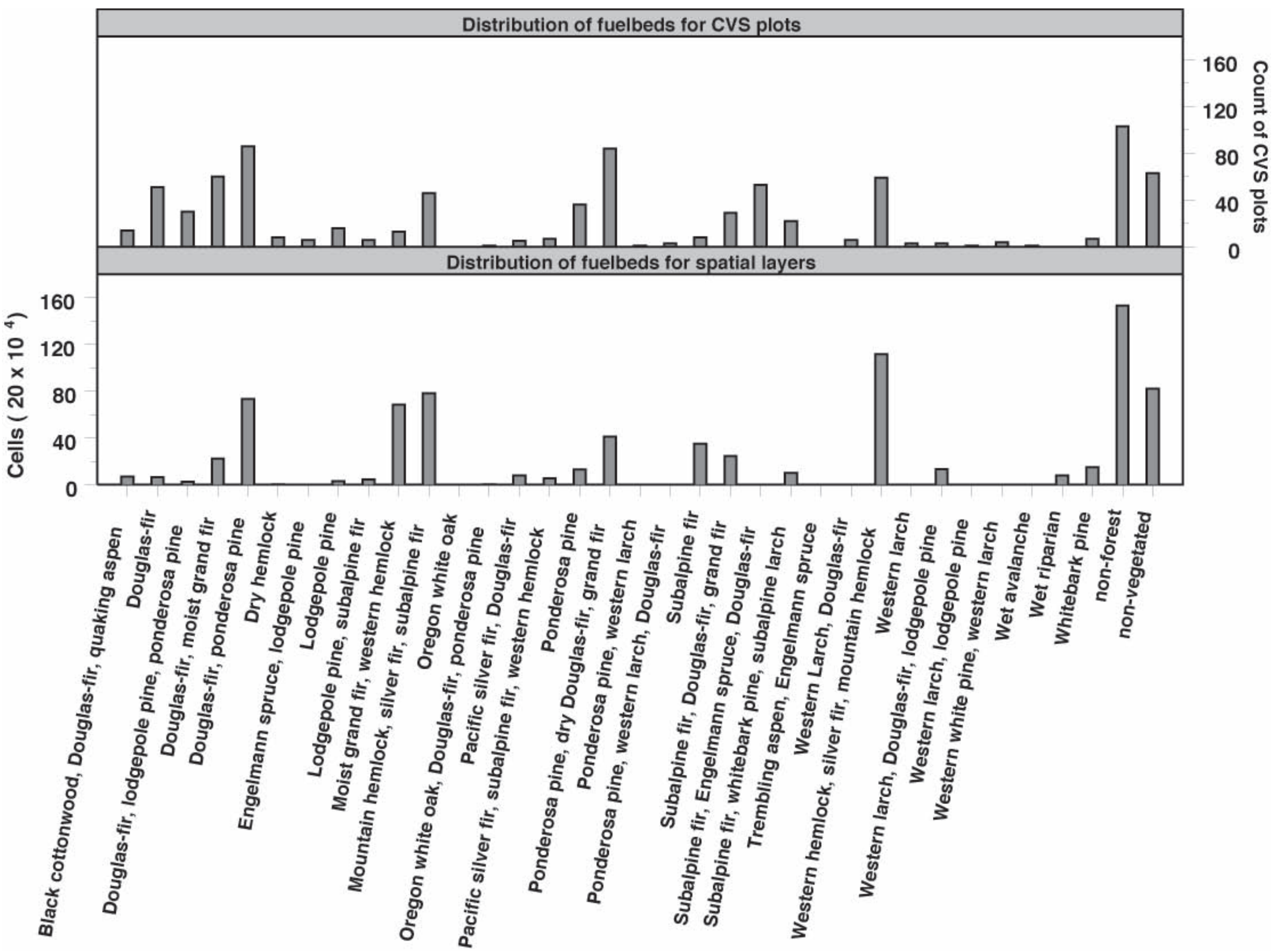

Figure 5—A comparison of fuel bed distributions from two sources on the Wenatchee National Forest, 835 CVS plots and remotely-sensed data.

the only rules amenable to this adjustment represented a small enough number of cells that the distributions changed only slightly toward lesser bias.

Validation with the CVS plots on the ONF indicated that the fuel bed classification process better captured the spatial distribution of fuel beds on the ONF than on the WNF. The distribution of fuel beds represented by the spatial data layers on the ONF was remarkably similar to that of the CVS plots with a few exceptions (figure 6). Classification of the spatial data layers over represented the "lodgepole pine" and "lodgepole pine, subalpine fir" fuel beds. Conversely two Douglas-fir fuel beds, "pure Douglas-fir" and "Western larch, Douglas-fir," occurred with much greater frequency in the CVS plots than in the classification of the combined spatial data layers.

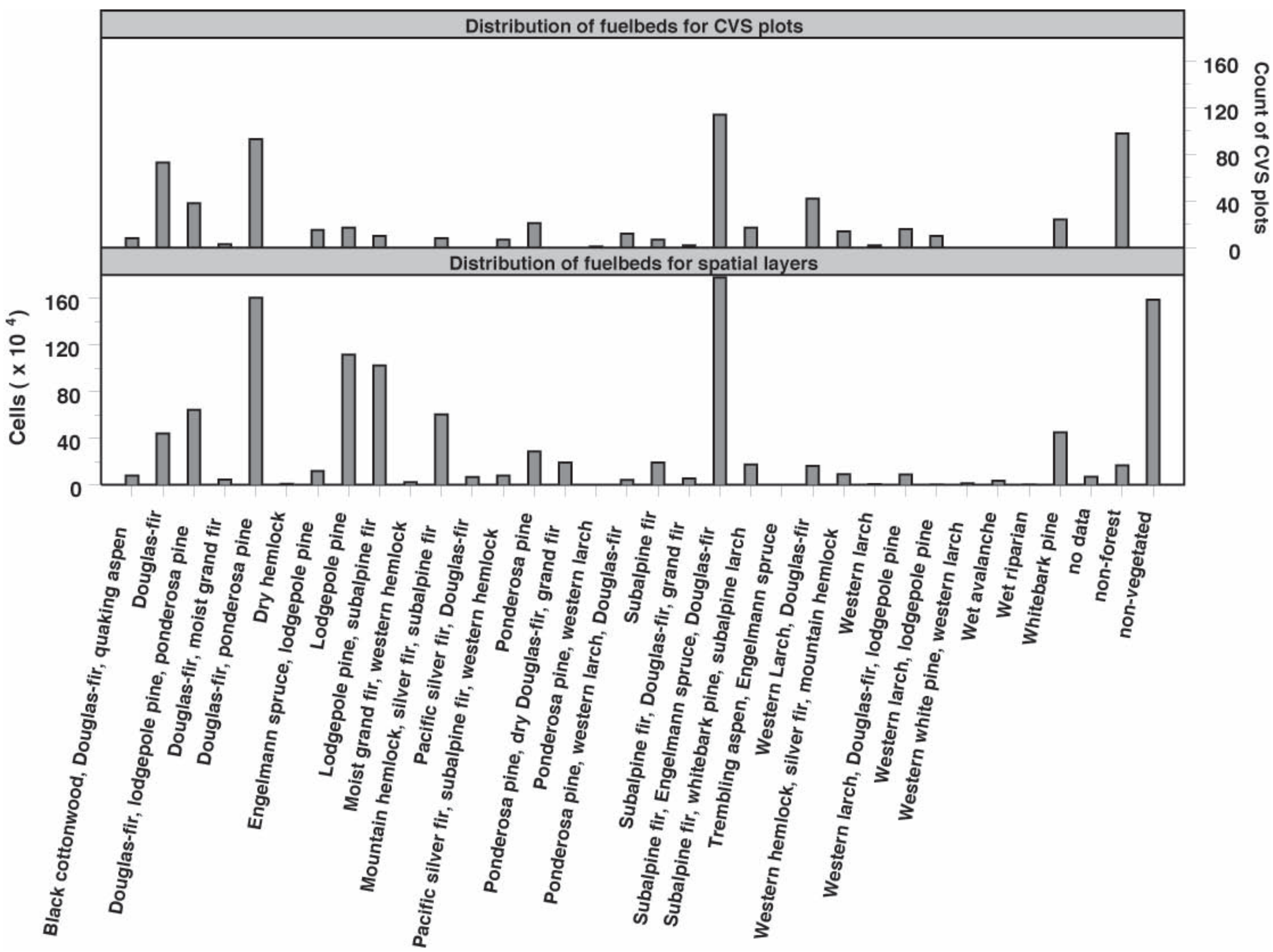

Figure 6—A comparison of fuel bed distributions from two sources on the Okanogan National Forest, 655 CVS plots and remotely-sensed data.

Discussion

We completed classification of FCCS fuel beds on two national forests using a rule-based method that takes advantage of spatial data layers of current and potential vegetation. In order to be useful for management and modeling applications, these fuel beds must be translated into fuel loads by fuel type (for example, canopy, live surface fuels, dead surface fuels, litter and duff). The FCCS has default values so the implementation of mapping fuel loads can proceed by assigning each cell its default value for each fuel category. Fuels are highly variable in space and time, however, so although this approach might produce unbiased estimates of mean fuel loadings, it clearly underestimates the variability of fuels across a region.

We can use high-resolution quantitative GIS layers that cover the WNF and ONF to quantify the attributes of each fuel bed. The Interagency Vegetation Mapping Project estimated both canopy cover and quadratic mean diameter (QMD) at 30-m resolution across the forest from LANDSAT TM imagery. The USU LANDSAT TM imagery included layers of canopy cover and stand size (d.b.h class) at 30-m resolution across the ONF. These layers provide structural information that can be linked to specific fuel beds (for example, table 1), thereby refining estimates of fuel loadings for each cell to the more precise default values associated with the specific fuel beds. This will be particularly valuable for quantifying fuels below the canopy layer—a problematic task in mapping fuels and vegetation in general (Keane et al. 2001).

Fuels are also highly variable over time, because of vegetation succession, disturbance, and land use. The FCCS includes a facility for incorporating "change agents" (Ottmar et al., in review) to account for modification of fuel beds by disturbance and management. This feature, along with the FCCS' basis in vegetation, enables straightforward updates of the mapped layers as new vegetation layers become available and disturbances are identified and mapped. The base maps we developed can be updated to implement a change agent for fuel beds assigned to cells affected by disturbance, or in some cases changed to a new general fuel bed, by incorporating spatial data layers on fire and insect disturbances and logging activities

Applications to Modeling and Management

Any attribute associated with a fuel bed can be mapped at the same resolution as the fuel bed. Not only can the default fuel loads for each of 16 categories of fuels be mapped, but also any output from the FCCS calculator can be similarly mapped. Mapped FCCS attributes can provide input layers for current and future modeling efforts at multiple scales. Managers can use these FCCS-based maps as planning tools for the national forest, because their forest-wide coverage with fine resolution matches the scale of forest plans (R. Harrod, personal communication, 2006). The ability to customize fuel beds within FCCS facilitates the quantitative evaluation of fuel-treatment scenarios across the landscape.

The hierarchical scheme of FCCS enables a crosswalk to existing and future spatial data layers using straightforward decision rules. Fuel bed attributes such as vegetation cover and fuel loads can likewise be matched to quantitative spatial data layers. Dynamic fuel mapping is necessary as we move into the future with rapid climatic and land-use change, and possibly increasing disturbance extent and severity. The rule-based methods we describe here are well suited for updating with new spatial data, to keep local and regional scale fuel assessments current and inform both research and management.

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Fuel Type Classification and Fuel Loading in Central Interior, Korea: Uiseong-Gun

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***Abstract**—The objective of this study is classification of fuel type and calculation of fuel loading to assess forest fire hazard by fuel characteristics at Uiseong-gun, Gyeongbuk located in the central interior of Korea. A database was constructed of eight factors such as forest type and topography using ArcGIS 9.1 GIS programs. An on-site survey was conducted for investigating vegetation and fuel loading. Forest distribution of Uiseong-gun is composed of mixed forest, about 43.7%, of coniferous trees such as* Pinus densiflora*, approximately 43.5%, and of broad-leaved trees like* Quercus variabilis*, 8.7%. In order of age class, trees are III-class (11~20 years) 57.6%, IV-class (21~30 years) 25.1% and II-class (1~10 years) 14.4%. By diameter at breast height (DBH) 82.5% are small diameter, 6~16 cm, and 14.9% of young trees are under 6 cm diameter. Most trees are are less than 16 cm DBH. Considering Korean forest characteristics this study led to a classification of ten fuel types. With the utilization of the data taken into account, this research, based on the existing forest type and forest soil map, categorized the 10 fire fuel types into three coniferous forests (C), one broadleaf forest (D), and one mixed forest (M), five fuel type forests in total. In shrub layers and below them, fuel load was found to be 7.64 t/ha in* Pinus densiflora *pure forest (C-1), 10.99 t/ha in the* Pinus densiflora*-middle stratum (C-2), 8.62 t/ha in the* Pinus densiflora*-substratum (C-3), 9.17 t/ha in the mixed forest (M), and 1.01 t/ha in the broadleaf forests (D). To categorize fuel types in drawing a forest fire fuel map, the research analyzed the relationship between the density of coniferous forests (C-1, C-2, and C-3), fuel load and forest soil conditions.*

Introduction

The USDA Forest Service developed a forest fire danger rating system consisting of two fuel models in 1964. The 1972 National Fire Danger Rating System (NFDRS) used nine fuel models (Deeming and others 1972). The 1978 NFDRS uses 20 fuel models (Deeming and others 1977). This research enables people to predict fire behavior in wildlife resources, thereby allowing one to evaluate and control potential forest fire damage. Rothermel's (1972) mathematical fire spread model enables quantitative prediction of fire behavior and forest fire danger rating. This mathematical model requires a description of fuel characteristics to calculate forest fire danger indices, namely, fire behavior potential. Data collection for fuel characteristics can be categorized as fuel models, which consist of four groups: grass, shrub, timber, and slash (from logging or fire or wind damage). Fire danger rating uses 20 fuel models. Thirteen fuel models are used in the fire behavior prediction and application (Albini 1976). Anderson (1982) provided photographs and descriptions of fuel models in particular areas, allowing users to use them

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with ease. Anderson also linked the fire behavior fuel models with fuel models in the National Fire Danger Rating System.

The Canadian Fire Behavior Prediction (FBP) system categorizes fuel types into five groups consisting of 16 types. The FBP system fuel types are quality-focused rather than quantity-focused, and are categorized into overstory layers (structure and composition of standing tree areas), shrub layers (surface and ladder fuel), and surface vegetation and duff layers.

This research seeks to use fuel management programs fit for Korean circumstances, taking into account geographical and ecological characteristics, and develop fuel models to be used in evaluating forest fire danger levels.

Methods

Study Area

Uiseong-gun belongs to North Gyeongsang Province, and is located in the middle inland area of Korea (Figure 1). The county's topography, except the area of Sinpyeong-myeon to the northwest, is not so rugged. The northwestern area is part of Taebaek Mountain Ridges, featuring overlapped mountainsides and forming highlands, but is in its old age stage and is relatively well-developed. The county is long east to west, and narrow north to south, forming a narrow rectangle. Major mountains include Mt. Geumseong (530 m), Mt. Seonam (879 m), and Mt. Bibong (672 m) to the southwest, as well as Mt. Bibong (579 m), Guksabong Peak (521 m) and Mt. Munam (460 m) to the Northeast. The county's forests consist of mixed forests, coniferous forests, and broadleaf forests. Pine tree forests represent over one-third of the forests. By forest type, mixed forests represent 43.7% of the total forests, coniferous forests 43.5%, and broadleaf forests 8.7%, thereby forming various forest types.

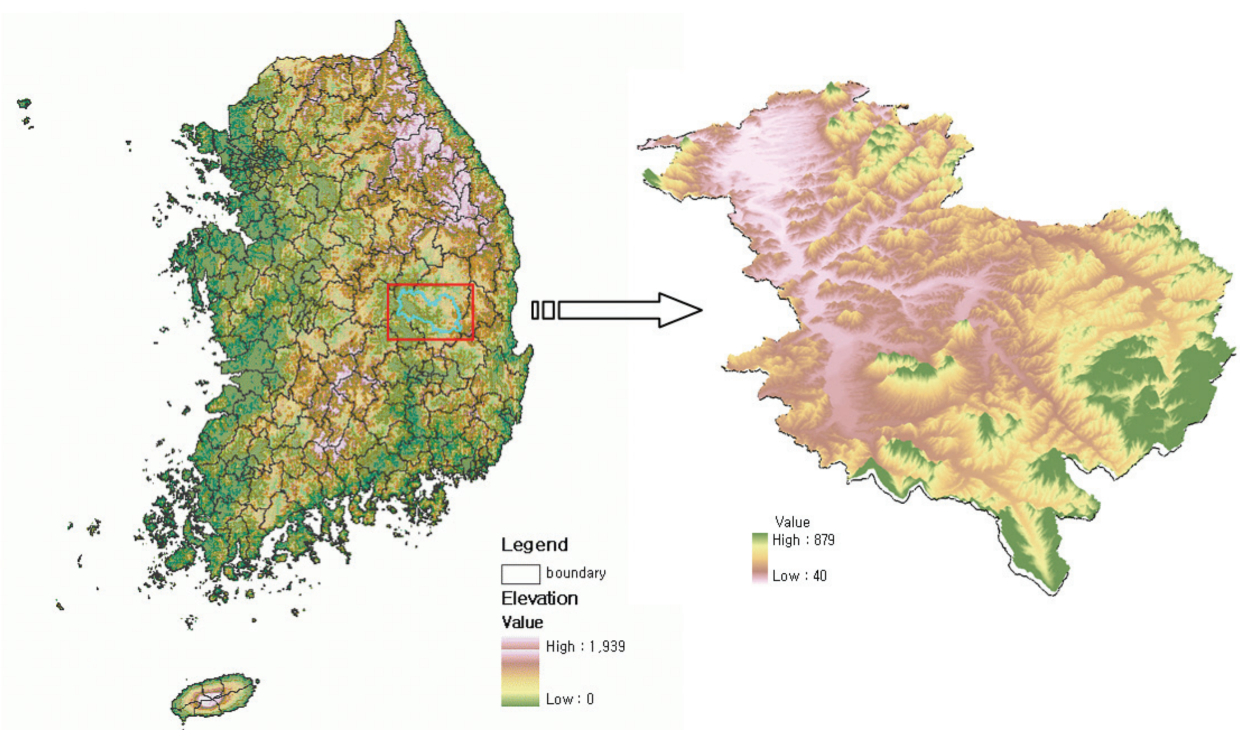


Figure 1—Site map of Uiseong-gun and on-site study area.

Field Methods

The recent-five-year (2001-2005) forest fire outbreak statistics by season indicates an annual average of 543 cases, and of these, in spring (March-May) alone, 364 cases broke out, representing 67% of the total. Thus, to accurately survey fuel load by forest fire type, on-site investigation was conducted in the spring, which is the driest season and has the greatest danger of forest fire.

To survey vegetation with the aim of categorizing forest fire fuel types, quadrates (10 m x 10 m) were installed in each vegetation community type classified by physiognomy and location conditions, and dominance and sociability by hierarchical level were measured using Braun-Blanquet (1964)'s phytosociological method, Z-M tradition. Regarding timbers and Korean dogwood existing in the installed quadrats, their species, tree height, crown base height, DBH, and crown diameter were measured. Also surveyed were each hierarchical level (timber, shrubs, and grass) and the thickness of fallen leaves that may influence forest fire ignition. Since fuel types within forest areas, even though the related trees are of the same kind, may have different structures according to topographical conditions, elevation, aspect, slopes and location coordinates were marked in the survey camp. To categorize Uiseong-gun's forest fire fuel types, live vegetation and dead fuel were surveyed in 46 survey zones. To estimate fuel load, fuel load in surface fuels in shrubs and litter were surveyed (Figure 2).

To survey fuel load, shrub forests were divided in a size of 2 m x 2 m, while grass, fallen leaves, fallen branches, and fruits were divided in a size of 1 m x 1 m. Also related fuels were collected on site and live load was measured. Each collected sample was dried in a drying oven, and dried load was measured again. On-site survey items are as follows (Figure 2).

- Vegetations survey: 10 m x 10 m quadrates
- Overstory: Tree height, crown base height, DBH, density
- Understory: Height of shrubs and grass layer, percent cover
- Fuel load: shrub, grass, fallen leaves, fallen branches
- Topographical conditions: elevation, slope, aspect

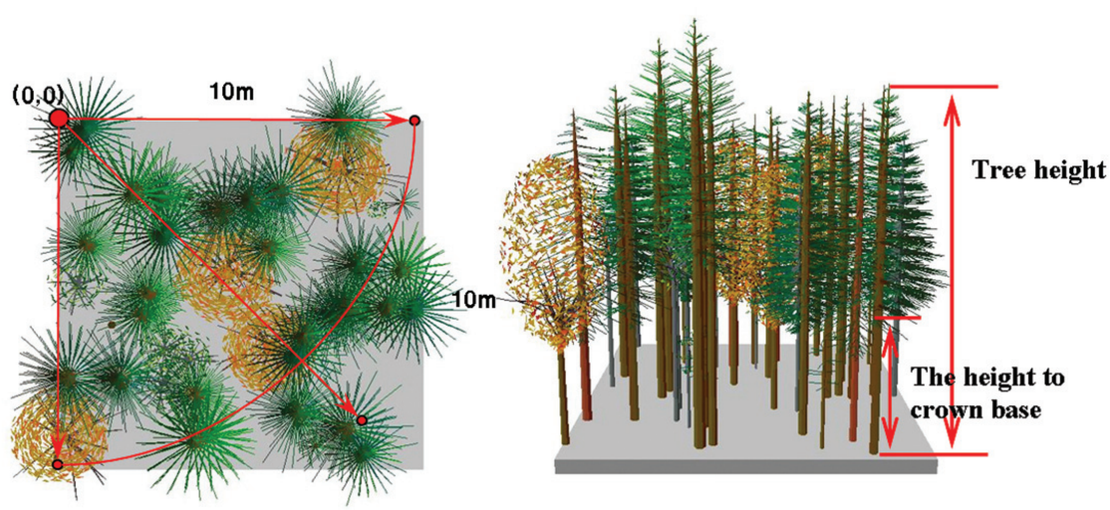


Figure 2—Field methods for fuel type classification.

Building of Database for Fuel Type Classification

To identify the distribution of Uiseong-gun's forest types, using a forest type map with a scale of 1:25,000 crafted by Korea Forest Research Institute and Korea Forest Service, maps by forest type and age class were developed. Using these forest type maps, survey points were selected to categorize forest fire fuel types, and taking account of the distribution ratios of forest types, the survey plan for the Uiseong-gun area was established. Also, to determine topographical features of Uiseong-gun, digital elevation models were crafted to manufacture a map featuring altitude, slopes and four directions (Figure 3). Also, since forest soil conditions have a great effect on the growth of trees and plants, (the map) reflected soil types to be used as reference data in categorizing forest fire fuel types. In this research, to distinguish the fuel type of pine tree forests, which have the highest danger of forest fire, soil types were extracted from the forest type map, and the relationship between the density and fuel load by soil type was analyzed.

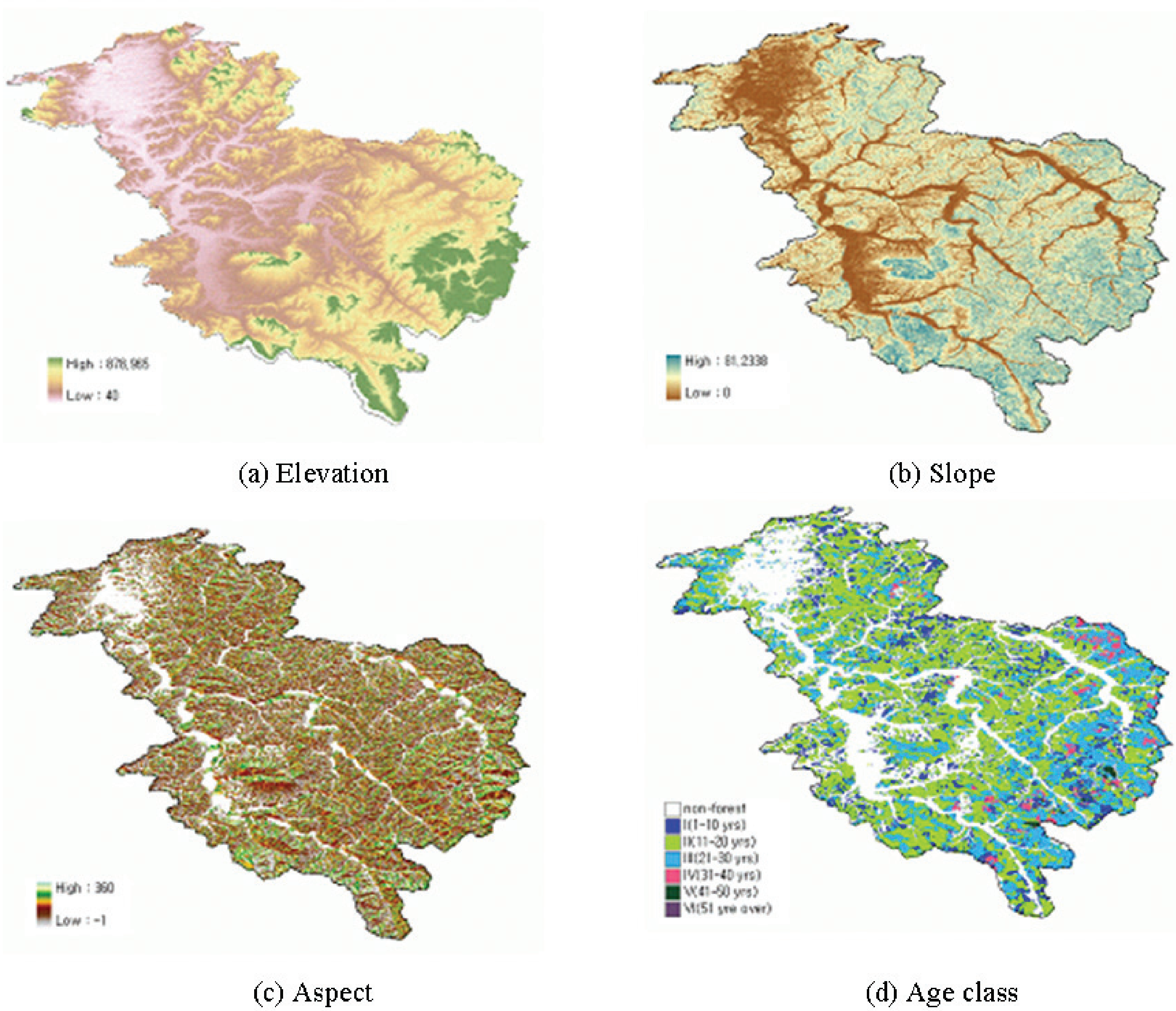


Figure 3—Topographical and forest conditions in Uiseong-gun.

Results and Discussion

Forest Type and Topographic Information

To structure databases designed for categorizing fuel types, using a forest digital map and a forest topographical map with a scale of 1:25,000, maps were crafted to reflect forest types, age class, forest type information by diameter class, DEM, slopes, aspect, and altitude, thereby determining the Uiseong-gun area's topographical information (Figure 4). In Uiseong-gun, mixed forests with coniferous and broadleaf forests represent the largest portion of the total at 43.7%, with pine tree forests accounting for 37.3%. Regarding distribution area by forest type, mixed forests represent 43.7% of the total, coniferous forests 43.5%, and broadleaf forests 8.7% (Table 1). By age class, the third-age class represents 57.6%, 4th-age class 25.1%, and 2nd-age class 14.4%, showing most of forests (72%) consist of forests under 30 years old (Table 2). Regarding distribution by diameter class, small-diameter trees account for 82.5%, thus making trees with the diameter of less than 16cm at the chest's height form the most of the forests (Table 3). Uiseong-gun's slopes are 20-25 degrees for 22.6% of the total area, 25-30 degrees for 40.3%, and over 30 degrees for 36.6%, showing most of the area has steep slopes.

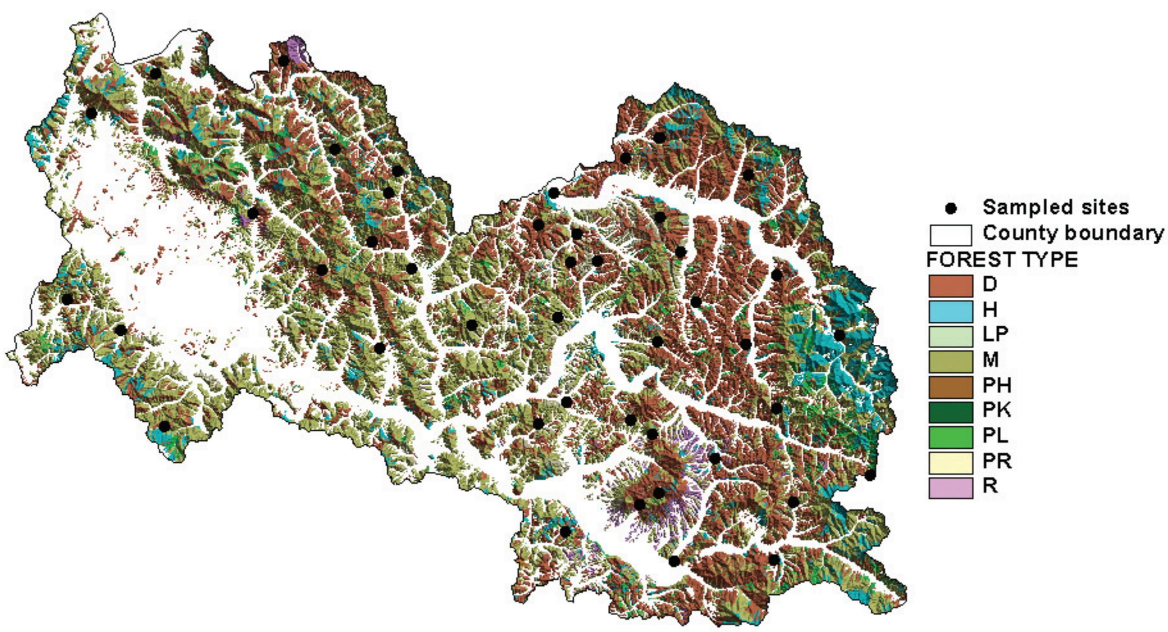


Figure 4—Forest type map in Uiseong-gun. D: *Pinus densiflora* Sieb. et Zucc; H: Deciduous forest; LP: Grass land; M: Mixed forest; PH: Unnatural deciduous forest; PK: *Pinus koraiensis* Sieb. et Zucc., Korean Pine; PL: *Larix leptolepis* (Sieb. et Zucc.) Gordon, Japanese Larch; PR: *Pinus rigida* Mill, Pitch Pine; R: Agricultural area within forest land.

Table 1—Forest distribution of Uiseong-gun by forest type map(1:25,000 scale).

Division	Code	Forest type	Area	Percentage	Total
			(ha)	- - - - - *(%)* - - - - -	
Coniferous Forest (C)	D,PD	*Pinus densiflora*	29,487.75	37.35	
	PK	*Pinus Koraiensis*	553.44	0.7	43.
	PL	*Larix leptolepis*	1,646.93	2.1	
	PR	*Pinus rigida*	2,713.03	3.4	
Deciduous Forest (D)	Q	*Quercus* sp. forest	108.72	0.1	
	PH	Unnatural deciduous forest	213.35	0.3	8.7
	H	Deciduous forest	6,543.59	8.3	
Mixed Forest (M)	M	Mixed forest	34,542.22	43.7	43.7
Open Land (O)	F	Cutover	7.32	0.0	
	O	Area of canopy cover 30% below	263.18	0.3	2.4
	E	Devastated region	2.95	0.0	
	LP	Pasture	52.6	0.1	
	L	Agricultural area	1,599.46	2.0	
Others	R	Agricultural area within forest land	1,372.57	1.7	1.7
	W	Stream	1.28	0.0	
	Others	—	0.62	0.0	
Total			**79,109.01**	**100**	**100**

Table 2—Distributed area by age class.

Age class	Area	Percentage
	(ha)	*(%)*
2 Class	10,944.95	14.4
3 Class	43,635.66	57.6
4 Class	19,007.94	25.1
5 Class	1,951.14	2.6
6 Class	243.39	0.4
Total	75,783.08	100.0

Table 3—Distributed area by diameter class.

Diameter class	Code	Area	Percentage
		(ha)	*(%)*
Sapling	0	11,314.75	14.9
Small	1	62,605.08	82.5
Medium	2	1,922.31	2.5
Large	3	55.70	0.1
Total	—	75,897.84	100.0

Forest Soil

As surveyed from the forest map, Uiseong-gun's forest soil area covers about 760,000ha, accounting for 65% of its total area. By soil attribute, dry brown forest soil accounts for 35.6%, slightly dry brown forest soil 31.2%, and moderately moist brown forest soil 15.9%, showing most of the forest area is brown forest soil (Table 4). Uiseong-gun's forest soil types are shown in Figure 5.

Table 4—Status of forest soil type in Uiseong-gun

Forest soil type	Percent of area
Dry brown forest soil (B1)	35.56
Slightly dry brown forest soil (B2)	31.18
Moderately moist brown forest soil (B3)	15.91
Slightly wet brown forest soil (B4)	0.34
Dry dark red brown forest soil (DRb1)	4.36
Slightly dry dark red brown forest soil (DRb2)	5.30
Slightly eroded soil (Er1)	3.22
Hardly eroded soil (Er2)	0.02
Lithosol (Li)	2.27
Red forest soil (R)	1.64
Dry reddish brown forest soil (rB1)	0.02
Slightly dry reddish brown forest soil (rB2)	0.19

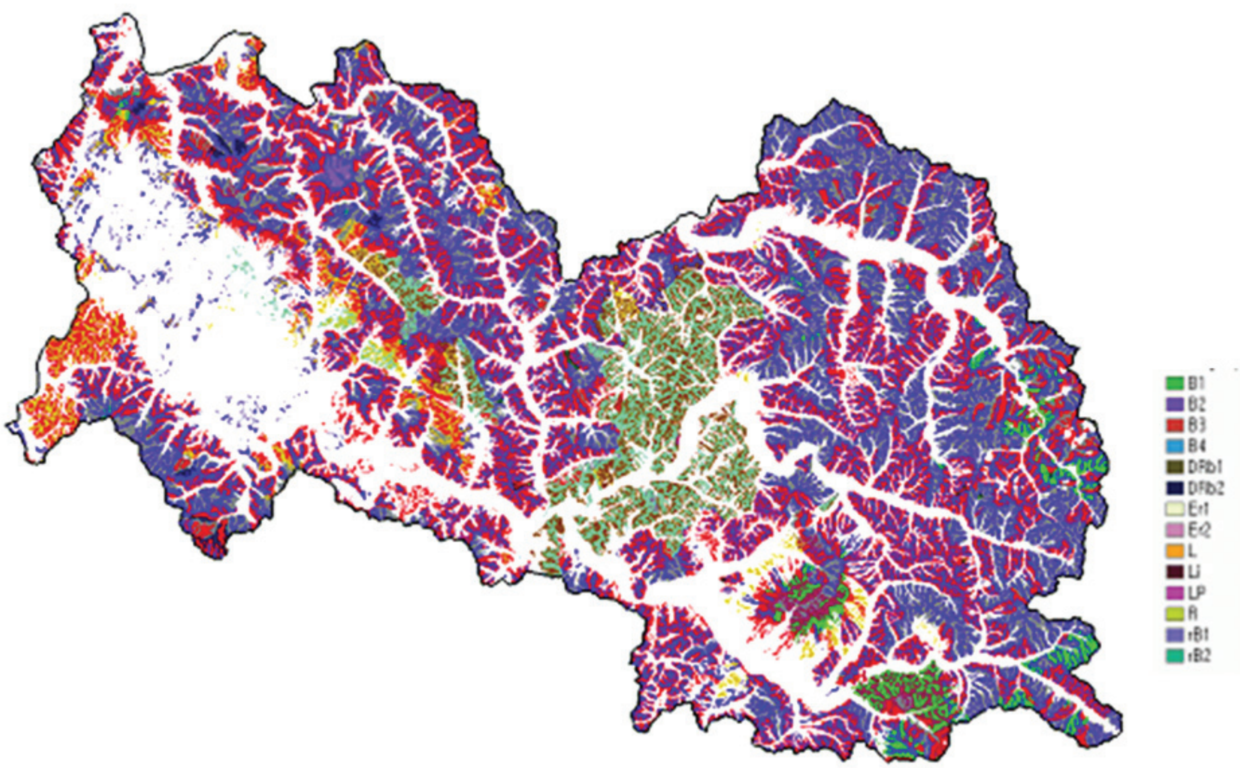


Figure 5—Forest soil type of Uiseong-gun.

Fuel Type Classification

Vegetation data gathered from on-site surveys were analyzed, thereby categorizing forest fire types by 10 items. To categorize forest fire types, based on the density of pine tree forests which are vulnerable to forest fire and have a wide distribution, dense and sparse areas were initially divided, and then four types were divided by the hierarchical level of pine trees. Also, one coniferous forest, one broadleaf forest and one mixed forest were divided. On-site-based forest fire types are divided as shown in Table 5. On the basis of Table 5 the results of vegetation survey classified by ten fuel types are shown in Table 6.

The ten forest fire types from on-site surveys are based on currently existing forest types, density of forest areas, and vegetation structures by hierarchical level, thus presenting limitations in using these forest fire types, categorizing fuel types in the whole survey areas, and crafting a fuel type map. Thus, to craft a fuel type map and put it to practical use, existing available forest type maps, forest soil maps, topographical data, satellite image data and others should first be used to categorize fuel types. This research first took account of cost and time in structuring databases as well as practical usage. A categorization of Uiseong-gun's forest fire types is based on forest type maps and forest soil maps, categorized as ten fuel types and reduced to five fuel types: three coniferous forest types (C), one broadleaf forest (D), and one mixed forest (M). Of these, pine tree forests which are the most vulnerable to forest fire are segmented into sub groups on the basis of forest types and hierarchical structures. The adjusted forest fire fuel types of Uiseong-gun are shown in Table 7.

Fuel Load Each Fuel Types

The type and strength of a forest fire may vary according to fuel load, size, and distribution, as well as depth of the fuel bed, fuel moisture, moisture of extinction and other conditions in the forest area. Thus, taking account of features of Korea's forests, pine tree forests which are the most vulnerable to forest fire were surveyed by hierarchical structure. As a result, in shrub levels, grass levels, fallen leaves, fallen branches, cones and other levels below the shrub levels, fuel load (ton/ha) of surface flammable materials was found to appear the most in broadleaf forests, *Pinus densiflora*-middle stratum,

Table 5—Ten fuel type classifications by field survey.

Forest type	Density	Fuel type
Coniferous forest	-*Pinus densiflora* (dense): 3,000 trees/ha and above	*Pinus densiflora* (dense) *Pinus densiflora* (dense)-shrub-grass *Pinus densiflora* (dense)-shrub
	-*Pinus densiflora* (sparse): 3,000 trees/ha and below	*Pinus densiflora* (dense)-grass *Pinus densiflora* (sparse) *Pinus densiflora* (sparse)-shrub-grass *Pinus densiflora* (sparse)-shrub *Pinus densiflora* (sparse)-grass
Deciduous forest		Deciduous forest
Mixed forest		Mixed forest

Table 6—Survey inventory classified by ten fuel types.

	Overstory (over 8m)				Middle story (2-8m)				Shrub		Grass		Fuel loading					
Fuel Type	TH	DBH	CBH	DEN	TH	DBH	CBH	DEN	SH	%C	GH	%C	shrub	grass	leaf	twig	cone	Total
	(m)	*(cm)*	*(m)*	*(trees/ha)*	*(m)*	*(cm)*	*(m)*	*(trees/ha)*	*(m)*	*(%)*	*(m)*	*(%)*	- - - - - - - - - - - - - - - *(ton/ha)* - - - - - - - - - - - - - - -					
1	8.9	9.9	4.6	17.0	6.0	5.8	3.6	27.0	1.5	21.3	0.5	21.3	0.4	0.3	5.7	1.5	0.3	8.0
2	—	—	—	—	4.8	6.9	2.2	42.0	1.8	30.0	0.7	65.0	0.7	1.4	6.5	1.8	0.3	10.7
3	9.4	12.4	4.7	15.0	6.1	7.0	3.9	23.0	1.5	70.0	1.0	20.0	1.1	0.1	8.0	2.2	0.3	11.7
4	9.1	13.3	3.7	6.5	5.3	6.4	2.7	41.0	1.8	20.8	0.9	62.9	0.3	0.7	6.1	1.6	0.4	9.0
5	11.3	20.1	6.2	14.0	6.4	10.3	3.8	7.0	1.7	23.3	0.4	20.8	1.3	0.3	5.0	1.2	0.5	8.2
6	9.7	29.7	6.4	9.0	2.8	2.3	—	12.0	1.5	60.0	0.7	50.0	4.2	1.0	4.2	1.2	0.3	10.9
7	9.9	16.8	4.6	12.0	5.5	7.2	2.6	16.8	1.8	50.0	0.6	13.8	0.8	0.4	7.1	1.7	0.2	10.0
8	9.3	14.2	3.7	10.3	5.8	9.4	2.7	13.4	1.6	18.1	0.9	70.0	0.4	1.1	4.5	2.0	0.5	8.3
9	11.3	15.0	3.9	8.4	4.8	8.4	2.2	8.8	1.9	29.0	0.8	13.0	1.4	0.2	5.8	3.7	0.2	11.0
10	10.5	13.5	3.5	8.9	5.1	6.5	2.4	17.0	1.7	22.5	0.4	35.0	0.3	0.2	7.0	1.7	0.1	9.2

TH: tree height, DBH: diameter at breast height, CBH: crown base height,
%C: percent cover, SH: shrub height

Table 7—Fuel type classification justified in Uiseong-gun.

Description	Fuel types	Fuel type code
Coniferous trees such as *Pinus densiflora*	*Pinus densiflora* pure forest	C-1
	Pinus densiflora-middle stratum	C-2
	Pinus densiflora-substratum	C-3
Deciduous trees such as *Quercus variabilis*	Deciduous forest	D
Coniferous and deciduous trees mixed	Mixed forest	M

mixed forests, and *Pinus densiflora*-substratum in this order, and the least fuel load was found in *Pinus densiflora* pure forest (Table 8). Fuel load, in the case of *Pinus densiflora* pure forest (C-1 type), was measured at 0.95 t/ha in shrubs, 0.22 t/ha in grass, 4.87 t/ha in fallen leaves, 1.27 t/ha in fallen branches, and 0.46 t/ha in cones, totaling 7.64 t/ha. In the case of *Pinus densiflora*-middle stratum (C-2 type), shrubs were measured at 0.88 t/ha, grass at 0.70 t/ha, fallen leaves at 7.34 t/ha, fallen branches at 1.89 t/ha, and cones at 0.28 t/ha, showing relatively a greater total amount of fuel load at 10.99 t/ha. Fuel load in *Pinus densiflora*-substratum (C-3 type) totaled 8.62 t/ha, with shrubs standing at 0.52 t/ha, grass at 0.89 t/ha, fallen leaves at 5.16 t/ha, fallen branches at 1.73 t/ha, and cones at 0.37 t/ha, showing a relatively greater grass fuel load, compared with other fuel load types. On the other hand, mixed forests (M type) where pine trees and oak trees were evenly distributed showed 0.29 t/ha, 0.16 t/ha, 6.98 t/ha, 1.67 t/ha, and 0.15 t/ha for a total of 9.17 t/ha of fuel load, in shrubs, grass, fallen leaves, fallen branches, and cones, respectively. Furthermore, fuel load in broadleaf forests (D type) totaled 11.01 t/ha, with fallen leaves and fallen branches standing at 5.78 t/ha and 3.68 t/ha, respectively, thus showing the greatest fuel load (Table 8).

Tree Density and Fuel Loading

To determine fuel features of C-1, C-2, and C-3, equivalent to 33 coniferous forests among 46 survey places, the relations between the density, fuel load below the shrub hierarchical level, tree height and diameter at the chest height were analyzed. The density of individual trees and fuel load in pine tree forests are displayed in a scatter plot in figure 6, which shows a distinctive "U" type on the basis of 3,000-4,000 trees per ha. In zones below 3,000 trees per ha, the more the density increased, the more the fuel load decreased. This is presumably because, in areas with a low density of pine trees, the age of pine trees was advanced at 3rd-4th age class (30-40 years), and biomass increased in forest areas as tree height was in proportion to diameter at the breast height. Also it is deemed that there was relatively greater volume and distribution ratio of thick branches in forest areas, thus increasing fuel load. And, fuel load decreased as the density of forests increased, presumably because competition between individual trees shortened tree height and diameter at the breast height, thus reducing biomass as well. In addition, artificial density management presumably decreased fuel load gradually. However, pine tree forests with 3,000 trees per ha showed trends that fuel load increased as density rose. These fuel features are characterized by low tree height and diameter at the breast height, and a high distribution ratio of small branches with small volume within forest areas. Mainly 2nd-3rd age class (20-30 years old) pine trees were packed closely, and the low hierarchical area had grass well developed, presumably providing a very high fuel load. These areas have not received density management and have been left abandoned, thus having great absolute amounts of fuel load. Thus, fuel load density management beginning with these areas should be conducted to reduce forest fire damage.

Fuel Types Classification by Forest Soil Types

Forest soil conditions have great impact on growth of trees and plants. According to soil moisture conditions, soil is categorized into dry soil, slightly dry soil and moderately moist soil. Dry soil includes B1 and Er1, slightly dry soil B2 and DRb2, and moderately moist soil B3. Thus, criteria for categorizing

Table 8—Survey inventory by fuel type in Uiseong-gun.

	Overstory (8m and over)					Middle story (2-8m)					Shrub		Grass		Fuel loading					
Fuel Type	TH	DBH	CBH	DEN	%C	TH	DBH	CBH	DEN	%C	SH	%C	GH	%C	shrub	grass	leaf	twig	cone	Total
	(m)	*(cm)*	*(m)*	*(trees/ha)*	*(%)*	*(m)*	*(cm)*	*(m)*	*(trees/ha)*	*(%)*	*(m)*	*(%)*	*(m)*	*(%)*	- - - - - - - - - - - - - *(ton/ha)* - - - - - - - - - - - - - -					
C-1	10.1	16.1	5.7	1500	67	6.2	8.1	3.7	1700	37	1.6	18	0.4	18	0.95	0.22	4.87	1.27	0.46	7.65
C-2	9.9	17.4	4.6	1200	66	5.2	6.9	2.8	2000	52	1.7	49	0.7	35	0.88	0.70	7.34	1.89	0.28	10.99
C-3	9.2	13.7	3.8	800	55	5.4	7.6	2.7	2800	51	1.6	22	0.9	64	0.52	0.89	5.16	1.73	0.37	8.62
M	10.5	13.5	3.5	900	54	5.1	6.5	2.4	1700	45	1.7	22	0.4	35	0.29	0.16	6.98	1.67	0.15	9.17
D	11.3	15.0	3.9	800	63	4.8	8.4	2.2	900	27	1.9	29	0.8	13	1.36	0.21	5.78	3.68	0.26	11.01

TH: tree height, DBH: diameter at breast height, CBH: crown base height,
%C: percent cover, SH: shrub height

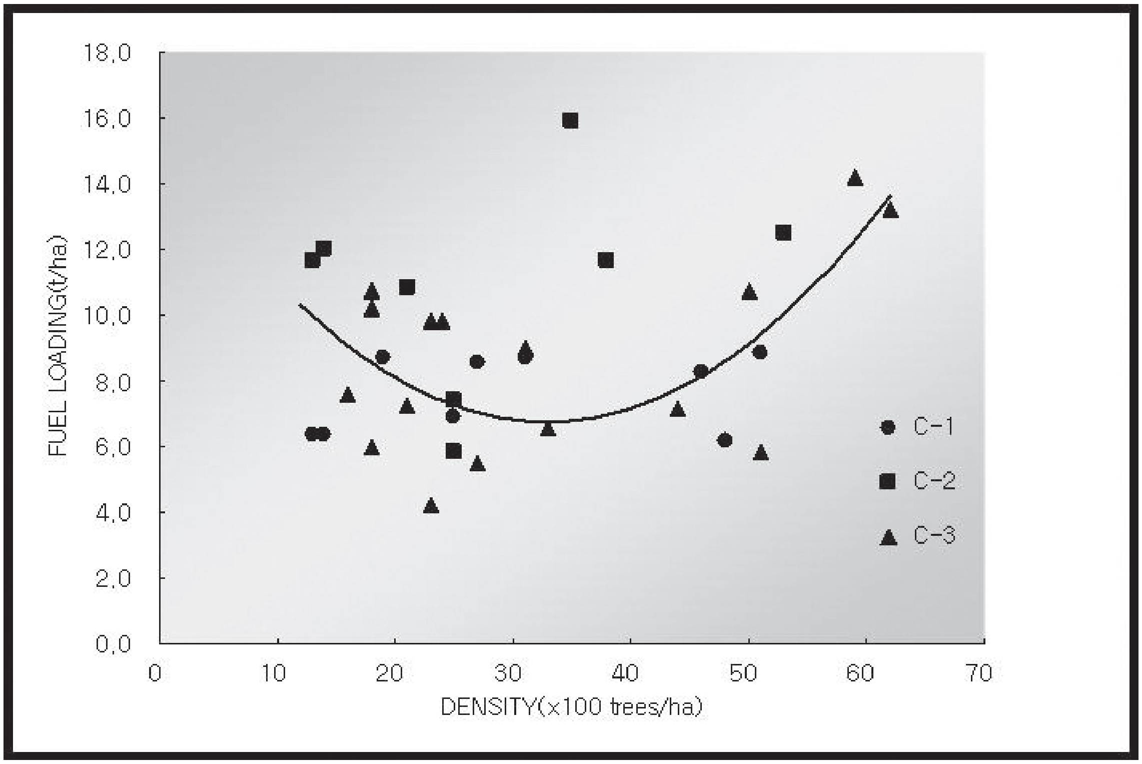


Figure 6—Density and fuel loading of the coniferous forest.

forest fire fuel types for coniferous forests (C-1, C-2, and C-3 types) can be established by utilizing soil types with soil moisture conditions reflected.

The dry soil B1, which is distributed chiefly in areas near ridgelines at the summit, upper areas of mountain slopes and other dry areas, accounts for about 70% of *Pinus densiflora* pure forest (C-1). In Figure 7, B1 soil maintains an average fuel load of 8.0 ton/ha, and the smaller the density is, the bigger the tree height and the diameter at the breast height are, thereby increasing the volume of fallen branches and amounts of fallen leaves and consequently presumably maintaining certain fuel load. With this type, the low hierarchical area usually remains a naked forest area, and thus, when a forest fire takes place, it will highly likely develop into surface fire.

Slightly dry soil B2, which is distributed chiefly at gentle-sloping summits and mountainsides in wind-hit areas, allows forest trees to have relatively good growth. Fuel load tends to decrease as the density of individual trees increases (Figure 7-B2). B2-soil areas saw mainly pine tree forests-low hierarchical type (C-3) distributed (60%), and the low hierarchical area was dominated by grasses, thereby boosting the ratio of grasses of fuel load. If a forest fire takes place in this case, grasses will play a role of ladder fuel, presumably creating danger of surface fire and crown fire in these areas.

Moderately moist soil B3 sees its fallen leaves decompose fast, mostly seeping into topsoil, and boosting the productivity of forest areas. Forest trees grow well in this soil. Fuel load of pine tree forests in B3 increases as density rises. C-1, C-2, and C-3 fuel types are evenly distributed, and the middle hierarchy has many broadleaf trees thus providing high possibility of developing into mixed forests. Pine tree forests-middle hierarchical type (C-2) are distributed at 50%.

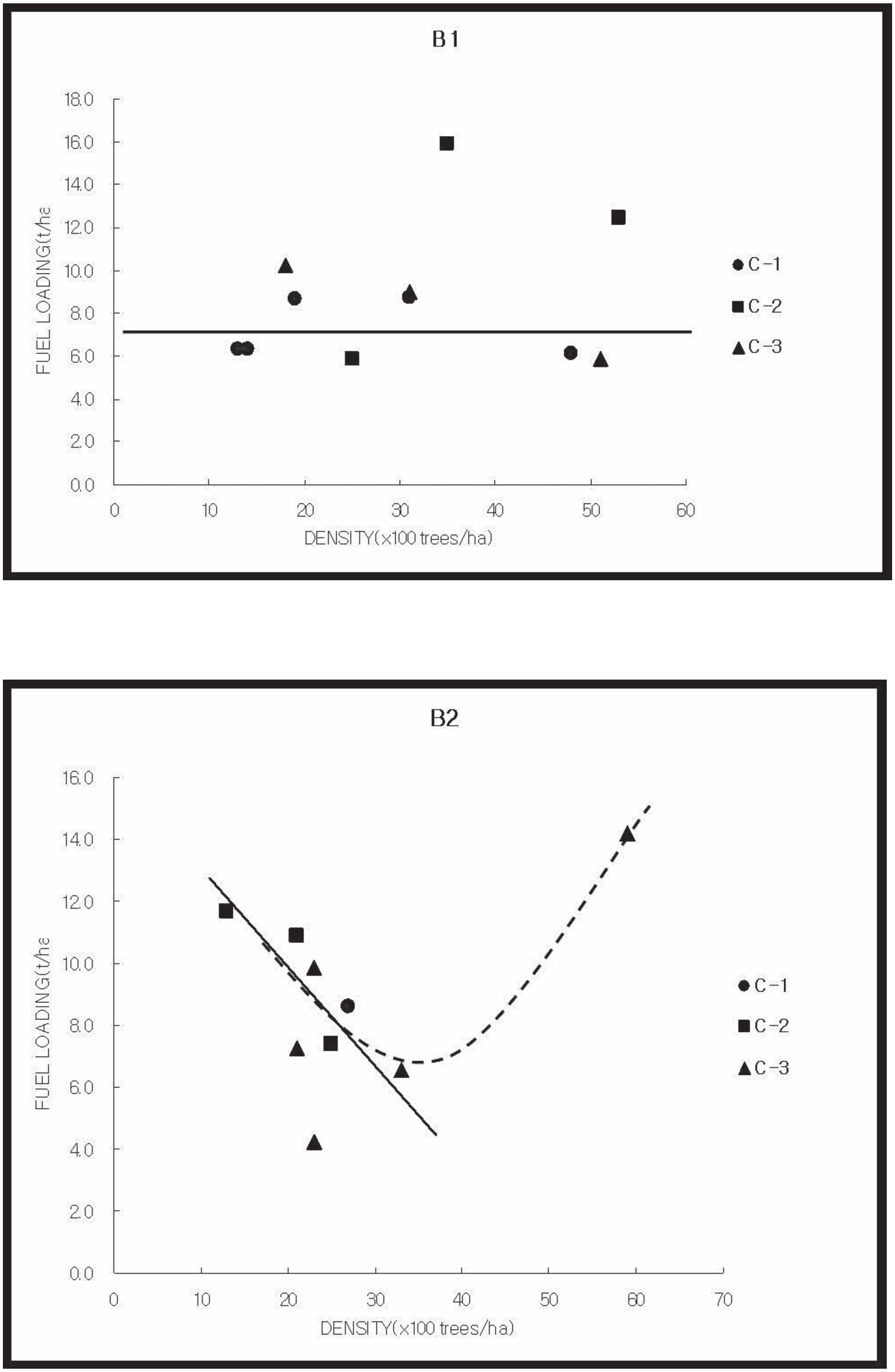
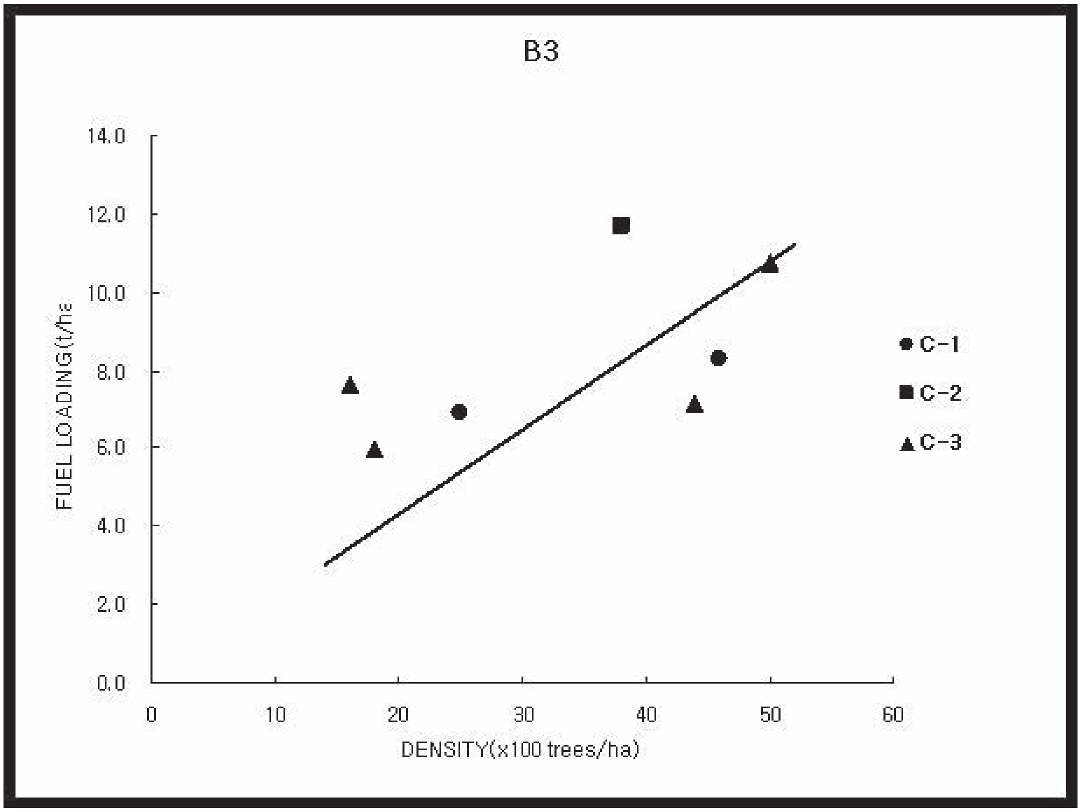


Figure 7—Density and fuel loading by forest soil of the coniferous forest. Dry Soil—B1, Er1; Slightly dry soil—B2, DRb2; Moderately moist soil—B3.



Conclusion

Forest fire occurrence probabilities and risk of fire spread in Korea are the greatest in coniferous forests. To ensure future efficient fuel management and make scientific and accurate prediction of forest fire occurrence and fire spread risk, basic surveys of fuel features of coniferous forests, particularly, pine tree forests, should be first conducted. Thus, to evaluate and quantify forest fire risk according to characteristics of forest fire fuel, fuel types should be categorized based on hierarchical structures by forest type, and the fire risk should be quantified on the basis of the survey of fuel load that allows one to estimate flammable amounts on topsoil. With the utilization of the data taken into account, this research streamlined forest fire fuel types from 10 to 5 (C-1, C-2, C-3, M, and H). In the future, nationwide-based forest fire fuel models will be developed by determining tree height and diameter at the breast height by density, and adding topographical factors such as mountain foot, mountainside, and summit in connection with fuel types.

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Understanding Ozark Forest Litter Variability Through a Synthesis of Accumulation Rates and Fire Events

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***Abstract**—Measuring success of fuels management is improved by understanding rates of litter accumulation and decay in relation to disturbance events. Despite the broad ecological importance of litter, little is known about the parameters of accumulation and decay rates in Ozark forests. Previously published estimates were used to derive accumulation rates and combined litter measurements, model estimates, and fire scar history data were used to derive a decay constant (k = 0.38). We used accumulation equations to demonstrate temporal changes in litter loading. For example, after a fire event that consumes nearly 100 percent of the litter, about 50 percent of the litter accumulation equilibrium is reached within 2 years, 75 percent within 4 years, and the equilibrium (99 percent accumulation) after approximately 12 years. These results can be used to determine the appropriate prescribed burning intervals for a desired fire severity. For example, fire history data show that the percentage of trees scarred, a surrogate for fire severity, is influenced by the length of historic fire intervals (i.e., amount of litter accumulated). This information will be incorporated into regional fire risk assessments and can be used as a basic knowledge of litter dynamics for both fire management planning and forest ecosystem understanding.*

Introduction

The Ozark Highlands lacks a general synthesis of the rate of litter accumulation and temporal variability of litter following fire events. Information on the temporal variability of fuels is needed by fire and forest managers in order to measure the success of management activities. In addition, information on litter accumulation is critical for modeling and monitoring of fuel loading and fire effects. This information is regionally specific and depends on the balance between rates of litter accumulation and decomposition (Olson 1963). Litter accumulation rates are controlled by vegetation type, decomposition rate, ecosystem productivity, and their interrelationships. Litter accumulation rates can be difficult to predict because of the high variability imposed by changes in species, tissues, vertical structure of vegetation, elevation, site, and time of year (Gosz and others 1972). Litter decays by leaching, physical weathering, faunal activities, and microbial consumption. Microbial consumption is the primary mode of decay and it is a process controlled by physical and chemical litter properties and climatic conditions (Meentemeyer 1978, McClaugherty and others 1985). Meentemeyer (1978) presented a general equation for predicting average annual decomposition rates (k) from actual evapotranspiration (AET) and leaf lignin contents.

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In order to provide general information for the Ozark region we synthesized data from existing studies and produced a model for predicting litter accumulation. In this paper we 1) provide a regionally averaged fuel accumulation equation for use in estimating fuel loading and 2) describe the long-term variation in Ozark fuel loading with fire history data. The objectives of the paper are to develop a quantitative relationship between litter amounts and time, and use this relationship to examine the effects of fire management on the accumulation and decay of litter.

Methods

Ozark Litter Accumulation and Decay Estimates

Estimates of litter accumulation and decay parameters were derived from four sources: 1) previous published studies, 2) actual litter loading measurements, 3) empirical litter relationships, and 4) analysis of historic fire intervals and tree scarring.

Previous Studies—In a study in the northern Ozarks, Kucera (1959) ranked litter from oaks (*Quercus alba, Q. rubra, Q. marilandica*) as being most resistant to decay, followed by sugar maple (*Acer saccharum*), shagbark hickory (*Carya ovata*), and American elm (*Ulmus americana*). At the same location, Rochow (1974) estimated a litter decomposition rate (k) of 0.35 for oak-dominated forest. More recently, Ryu and others (2004) arrived at a similar estimate for a larger portion of the Missouri Ozarks using an ecosystem productivity model (PnET-II) (Aber and others 1995).

Litter Loading Measurements—Missouri Ozark region litter loading data was gathered for many forested sites and time periods (table 1). Litter was collected using clip plot methods, dried to a constant weight, and reported on a dry-weight basis. In addition, we gathered associated data, including collection date (pre- and post-burn), dates of fires, number of previous fires, and physical plot attributes (slope, aspect, vegetation type, overstory basal area, and stand density). Variability in litter sample weights likely occurred due to collection by different investigators, years of collection, and forest conditions. When possible, we only used measurements that excluded the zone of highly decomposed material commonly called the humus or duff layer. We estimated the litter decomposition rate (k) using the equation developed by Olson (1963), where the annual production of litter is divided by the standing crop litter. The mass of annual litter production was estimated using mean litter loading values collected one year after burning. Estimates of the average standing crop (steady-state level) of litter were derived from litter masses that had accumulated for >20 years and were based on multiple measurements taken from many Ozark sites (table 1).

Empirical Litter Relationships—We also estimated litter decomposition rates using Meentemeyer's (1978) general equation, which incorporates lignin contents and actual evapotranspiration (AET). Average litter lignin content for the important Ozark tree species was derived from previously published studies. Tree species included black oak (*Q. velutina*), scarlet oak (*Q. coccinea*), white oak (*Q. alba*), post oak (*Q. stellata*), and shortleaf pine (*Pinus echinata*) (table 2). No lignin contents were obtained for hickories (*Carya* spp.). Though there is likely high variability in decomposition rates due to

Table 1—Data on oven dry-weights of litter from 35 Ozark Highlands sites. Forest structure codes and site information are given at the bottom of the table.

Site	Forest structure	n	Basal area (ft^2/ac)	Years accumulation	Litter (tons/ac)	Litter (tonnes/ha)	Source
Knob Noster S.P.	1	5	80	2	3.02	1.11	authors
HaHa Tonka S.P.	1	5	58	2	3.12	1.14	authors
Meremac S.P.	1	7	108	3	2.50	0.92	authors
Taum Sauk Mnt S.P.	1	7	52	2	2.90	1.06	authors
Bennett Spring S.P.	1	4	66	1	2.56	0.94	authors
USFS - Mark Twain	1	7	51	1	2.71	0.99	authors
University Forest A1	1	2	55	1	2.18	0.80	authors
Baskett WMA A1	2	9	na	1	1.56	0.57	Rochow 1974
Stegall Mtn.	1	3	38	2	2.76	1.01	authors
Chilton Creek 2003	1	26	na	1	2.00	0.73	Hartman 2004
Chilton Creek 1998	1	26	na	>20	3.40	1.25	Hartman 2004
University Forest B1	1	na	na	1	1.64	0.60	Scowcroft 1965
University Forest B2	2	na	na	>20	5.45	2.00	Scowcroft 1965
University Forest C1	2	na	na	>20	3.88	1.42	Meier 1974
University Forest D1	2	na	na	>20	6.10	2.23	Paulsell 1957
Jerktail Mtn.1	2	18	96	>20	5.77	2.12	authors
Jerktail Mtn. 2	2	6	67	>20	4.17	1.53	authors
Powder Mill 1	2	10	82	>20	4.97	1.83	authors
Powder Mill 2	2	6	93	>20	4.00	1.47	authors
Akers1	2	14	99	>20	3.49	1.28	authors
Akers2	2	10	86	>20	3.88	1.42	authors
Alley Spring	2	6	93	>20	3.76	1.38	authors
Bay Creek 1	2	6	90	>20	3.84	1.41	authors
Bay Creek 2	2	6	73	>20	4.13	1.52	authors
Black River 1	2	15	na	>20	3.02	1.11	Kolaks 2004
Black River 2	2	15	na	>20	3.19	1.17	Kolaks 2004
Black River 3	2	15	na	>23	2.92	1.07	Kolaks 2004
Coot Mtn.	2	6	103	>20	3.23	1.19	authors
Williams Mtn.	2	6	90	>20	6.53	2.40	authors
Wildcat Mtn.	2	8	93	>20	4.29	1.57	authors
Baskett WMA B1	2	102	129	>20	6.52	2.39	authors
Goose Bay Hollow	2	8	110	>20	5.44	2.00	authors
Dent & Iron Co.'s [a]	2	na	na	>20	6.60	2.42	Loomis 1975
Sinkin Exp. Forest 1 [a]	2	na	na	>20	6.20	2.28	Loomis 1965
Sinkin Exp. Forest 2 [b]	2	na	30	>20	5.00	1.84	Crosby and Loomis 1968
Mean maximum accumulation (>20 years accumulation)					4.57	1.68	

forest structure: 1 = savanna/woodland, 2 = forest
na = not available
[a] contains organic matter
[b] shortleaf pine plantation

Table 2—Lignin contents of important Ozark forest species.

Species	Lignin content (%)	Source
Quercus velutina	25.70	Martin and Aber 1997, Aber (online data)
Quercus coccinea	18.70	Washburn and Arthur 2003
Pinus echinata [a]	25.50	Washburn and Arthur 2003
Quercus rubra [b]	23.43	Martin and Aber 1997
Quercus rubra and *Quercus alba*	23.48	Martinand Aber 1997
Mean	23.36	

[a] samples include *Pinus rigida* litter.
[b] samples include *Acer rubrum* litter.

variability among sites, climatic conditions (for example AET), and numerous vegetation assemblages, we utilized a multi-species average of lignin contents for the region since our aim is to develop a better general understanding of litter dynamics in the Ozarks. We obtained AET estimates for the Ozark Highlands region from the Global Hydrologic Archive and Analysis System (GHAAS). Data were 0.5 degree gridded average annual AET estimates given in millimeters per year (Vörösmarty and others 1998). We averaged long-term grid means for the Ozark region to get a mean regional AET value.

Historic Fire Intervals—Historic fire intervals were derived from four previously constructed published and unpublished fire scar history studies in the Ozarks. Study sites were located in Shannon County, Missouri and included Stegall Mountain (Guyette and Cutter 1997), Mill Hollow, MOFEP Site 3, and MOFEP Site 4 (Guyette and Dey 1997). Methods for sample collection, tree-ring crossdating, and fire scar dating can be found in several published studies (Guyette and others 2003, Stambaugh and others 2005). Site level fire scar chronologies were input to FHX2 software (Grissino-Mayer 2001) where fire intervals were calculated for each fire at each site as the number of years between fire events. Fire intervals were paired with the percentage of trees scarred in the fire year that ended each interval. The percentage of trees scarred was calculated as the number of sample trees scarred in a given year divided by the number of recorder sample trees in the same year. All data were pooled into a single dataset with 111 paired observations of fire intervals and percentage of trees scarred. Due to the changing characteristics of the anthropogenic fire regime (Guyette and others 2002), we only used data from the period A.D. 1700 to 1850 in the analysis. This period was selected because it is well replicated (9-20 recorder trees at any given year) at all sites and because there exists high variation in the length of fire intervals. We used non-linear regression (exponential equation) to describe the variability in the percentage of trees scarred from fire intervals. We assumed that the variation in percentage of trees scarred is related to fuel accumulation. Based on this assumption, an exponential function should approximate the litter accumulation rate and the exponential term of the regression model would be an estimate of litter decomposition rate (*k*).

Temporal Litter Variability Model

The mass loss of litter as a function of time is generally expressed as an exponential decay model (Bärlocher 2005, Olson 1963). The temporal litter variability for Ozark forests was described using an exponential decay function:

$$X_t = X_0 * e^{-kt},$$

where X_t is the amount of litter remaining after time t, X_0 is the initial quantity of litter, and t is time of accumulation. The estimated rate of litter decomposition ($k = 0.38$) was a mean derived from four different procedures (table 3). The mean standing crop of litter (4.57 tons/acre, see results on next page) was used to define maximum mass accumulation. We used the exponential decay function to describe the rate of accumulation of litter and the time required to reach maximum litter accumulation. Additionally, the equation was applied to historic fire event data from four Ozark fire scar history sites (Stegall Mountain, Mill Hollow, MOFEP Site 3, MOFEP Site 4) in order to reconstruct past temporal variability in litter loading. Using fire scar chronologies, the model was initiated at the first year of record. Fire event

Table 3—Litter decomposition rates (*k*) from the Missouri Ozark Highlands.

Method	*k*	Source
Litter loading measurements	0.46	this paper
Climate/leaf lignin model	0.64*	this paper
Historic fire intervals	0.34	this paper
Litter loading measurements	0.35	Rochow 1974
Climate/leaf lignin model	0.35	Ryu and others 2004
Mean	0.38	

*not used to calculate mean

years were used to reset the litter accumulation model to zero. Accumulation following fire events assumed 100 percent fuel consumption and a constant weight of annual litterfall.

Results

Ozark Litter Accumulation and Decay Estimates

Litter Loading Measurements—The mean mass of annual litter production was 2.11 tons/acre (n = 6, s.d. = 0.47) or 0.77 tonnes/hectare. The mean standing crop of litter was 4.57 tons/acre (n = 24, s.d. = 1.22) or 1.68 tonnes/hectare. Based on the ratio of mean annual production of litter to the mean standing crop, the estimated litter decomposition rate (k) was 0.46.

Empirical Litter Relationships—Average percent lignin contents of litter for the important Ozark overstory forest tree species (table 2) was 22.63%. AET values ranged from 675 to 760 mm/yr and the mean was 712 mm/yr. Based on Meentemeyer's (1978) equation the estimated litter decomposition rate (k) ranged from 0.59 to 0.69.

Historic Fire Intervals—The relationship between the percentage of trees scarred in a fire event and the preceding fire interval (years since last fire) was established using the non-linear equation:

$$\text{percent trees scarred} = 13.8 + 7.72\,(\ln[\text{fire interval}]),$$

where the fire interval is years since last fire event (model $r^2 = 0.21$, intercept and variables significant $p<0.0001$, n = 111). Although the fire-free interval model explained only about one-fifth of the variance, the model and variables were highly significant. The form of the equation resulted in an exponential term (litter decomposition rate (k)) of 0.34.

Temporal Litter Variability Model

The temporal litter variability for Ozark forests was described using an exponential decay equation and is presented in terms of percent accumulation (eq. 1) and mass accumulation (eq. 2).

$$\text{Percent accumulation} = 100 - (100e^{-0.38t}) \qquad \text{(eq. 1)},$$

$$\text{Mass accumulation} = 4.57 - (4.57e^{-0.38t}) \qquad \text{(eq. 2)},$$

where t is the years of litter accumulation. The equation predicts that litter accumulates to 25 percent, 50 percent, and 75 percent of maximum accumulation at approximately 1 year, 2 years, and 4 years, respectively (fig. 1). An equilibrium accumulation (99 percent) is reached at approximately 12 years. In terms of mass accumulation, roughly one ton of litter per acre is accumulated per year up to 3 years post-fire (fig. 1).

The litter accumulation function showed important differences in litter accumulation with burning frequency (fig. 2). For example, annual burning allows a maximum of 32 percent of the total litter to accumulate. A burning frequency of 5 years allows a maximum of 85 percent of the total litter to accumulate, while a burning frequency of 10 years allows a maximum of 97 percent of the total litter to accumulate. In terms of litter loading, the difference between annual and 5-year burning frequency is over two times greater than the difference between 5-year and 10-year burning frequencies.

The effects of variable burning frequencies were further exhibited by a reconstruction of long-term Ozark litter loading (fig. 3). The long-term variation in historic fuel loading is striking and a result of frequent anthropogenic ignitions. Prior to EuroAmerican settlement (pre-1800), fuel loading was both spatially (between sites) and temporally variable. Comparisons between sites show that Stegall Mountain has undergone conditions of continuous burning and rapid fuel replenishment. Mill Hollow and MOFEP Sites 3 and 4 underwent prolonged frequent fires (1-3 years) that lasted most of the 19th century and had a long-term effect on minimizing fuel loading. Mean fuel loading of the four sites was 2.91 tons/acre prior to 1800 and 1.45 tons/acre from 1800-1900. Since about 1930 to 1940, the effects of fire suppression has resulted in maximum litter loading and lowered temporal litter variability. An exception is Stegall Mountain, where prescribed burning management has been in practice since about 1980.

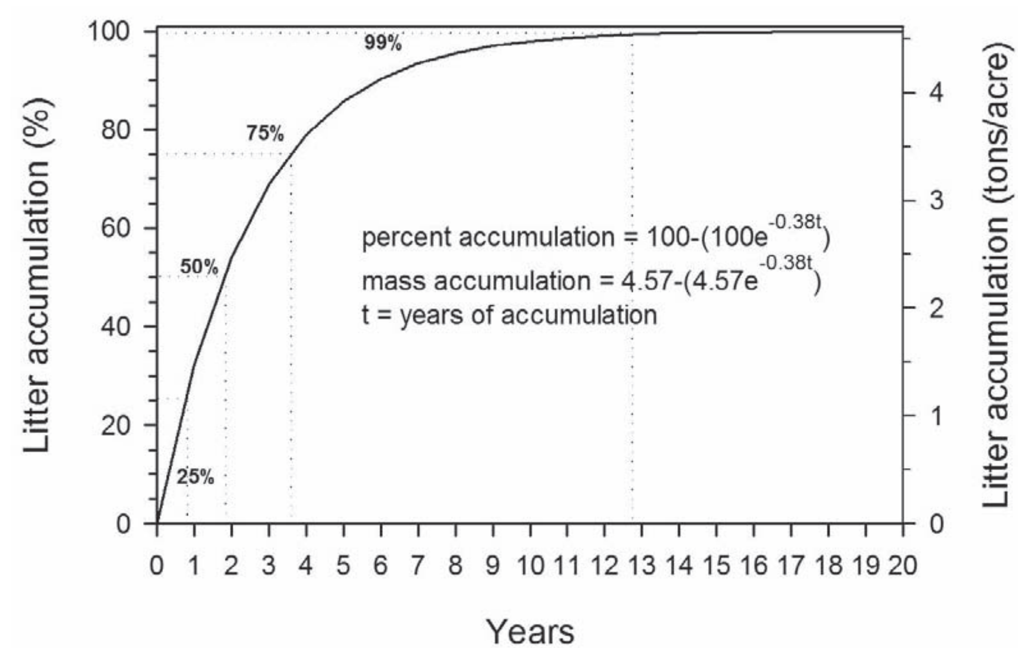

Figure 1—Plot illustrating a litter accumulation function in terms of percent of maximum and mass for forests of the Ozark Highlands, Missouri. The decomposition constant (*k*) was based on the mean from multiple sources and methods (table 3).

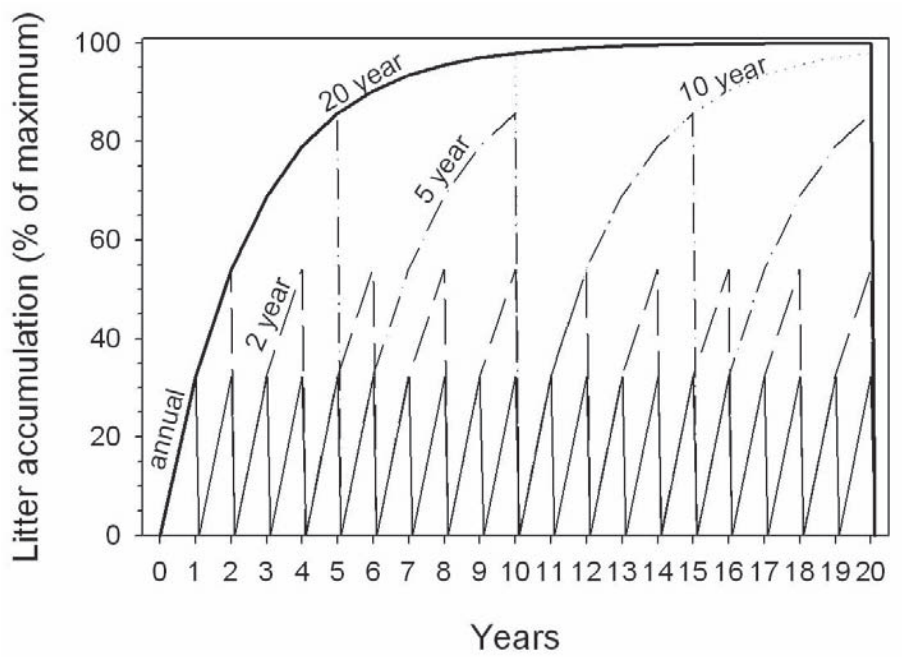

Figure 2—Litter accumulation dynamics with litter removed by fire (or other means) at different but regular intervals. Given here are litter accumulation patterns for annual fire intervals (solid fine line), 2-year fire intervals (short dashed line), 5-year fire intervals (dot dashed line), and a single 20-year interval (solid bold line).

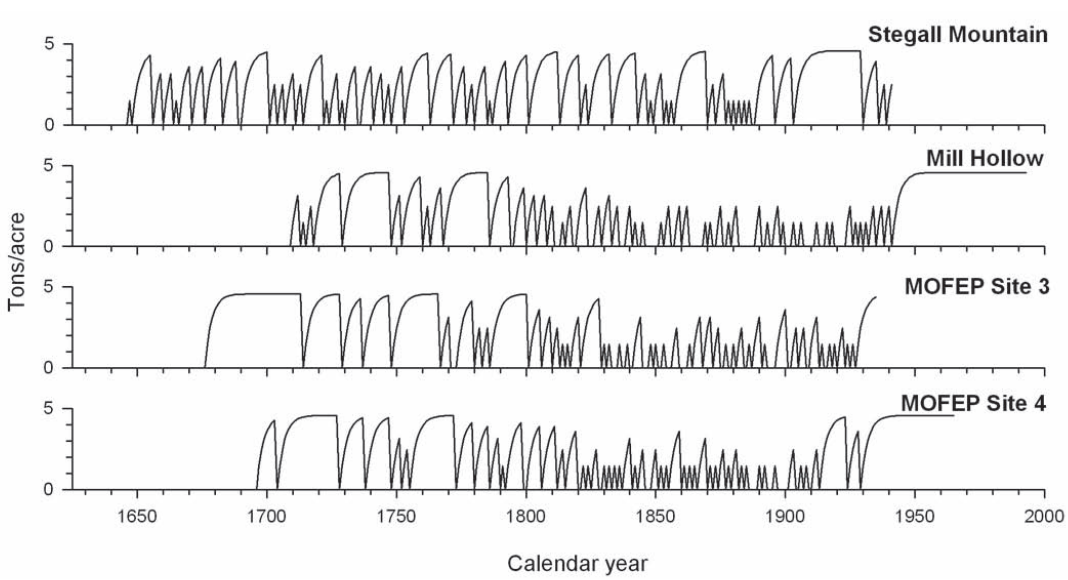

Figure 3—Litter loading reconstructions for four forest sites in the Ozark Highlands, Missouri. Reconstructions are based on fire scar history data and a litter mass accumulation function (fig. 1). Site reconstructions begin and end at different calendar years based on the period of fire scar chronology records.

Discussion

Fire suppression policies of the past 75+ years have altered Ozark forest ecosystems, often in ways that are not fully understood at this point in time. From fire scar studies, we know that much of the Ozarks landscape burned relatively frequently (8-15 years) for at least 200 years prior to Euro-American settlement. The natural communities that developed during that time are now changing, and restoration efforts often include the reintroduction of fire, despite a lack of quantitative information on how fire might behave under the conditions resulting from years of fire suppression. One of the many ways in which fire suppression has affected Ozark forests is by altering the nature of fuels at the forest floor, though there has not previously been a way to quantify these changes. In this paper, we present a litter accumulation model specific to the Ozark region, which we hope will improve our general understanding of the temporal variability in litter accumulation and our ability to manage fuels effectively in the Ozarks. The litter accumulation equations provide managers and scientists with a standard of expected fuel loading, the potential effects of different burning frequencies on fuel accumulation and loading, and estimates of the historic variability in fuel loading at four Ozark sites.

Estimates of temporal changes in fuel depend primarily on the litter decomposition rate (k) and level of maximum litter accumulation. The best estimates of litter decay and accumulation in the Ozarks were based on litter loading measurements and the historic fire record. We chose not to include the value of k derived from mean annual AET and lignin contents as the estimate was extremely high ($k = 0.64$). Though litter decomposition rates differ from year to year due to changing conditions (for example climate, species, forest density), we felt that the value was a gross overestimate and outside of a plausible range of rates (Ryu and others 2004). The increased rate of decomposition of mixed-species litter (Gartner and Cardon 2004) was unaccounted for, and may be one important reason why Meentemeyer's equation yielded a decay constant much higher than other estimates.

The rapid accumulation of litter following disturbance events likely leads to large differences in burn coverage and fire behavior between fire frequencies of 1, 2, and 3 years. To illustrate this point Behave Plus 3.0.1, fire behavior prediction software, was used to estimate the different fire rates of spread and flame lengths between fuel accumulation rates at 1, 2, and 3 years (table 4). All else equal, fires occurring at 10-year intervals versus 20-year or longer intervals may not differ significantly in behavior or severity (percent trees scarred)

Table 4—Behave Plus prediction of fire behavior using litter accumulation rates from this study. Behave Plus was run using fuel model 9 and 1 hour fuel loading was adjusted according to accumulation rates.

Litter Accumulation Rate	Midflame Windspeed (mph)	Slope (%)	1hr % Moisture Content	10hr % Moisture Content	Rate of Spread (chains/hr)	Flame Length (ft)
1 yr (25% max)	10	5	5	7	24.8	3.3
2 yr (50% max)	10	5	5	7	29.4	4.5
3 yr (65% max)	10	5	5	7	30.1	4.9
10 yr (97% max)	10	5	5	7	29.5	5.3
20 yr (100% max)	10	5	5	7	29.6	5.3

because the level of litter accumulation is similar (table 4). One important factor in surface fire behavior is litter moisture content which can be highly variable by aspect and drought condition (Stambaugh and others, in press). Litter profiles can also be highly variable with dry litter on the surface covering a relatively moist "mat" of partially decomposed but identifiable leaves of the previous few growing seasons (Crosby 1961, Loomis 1975). Furthermore, although fuel loading following 10 and 20 years of accumulation may be marginal, important differences in the development and conditions of the underlying litter profile likely exist.

In addition to the quantification of accumulation and decay rates, the reconstruction of long-term litter loading under different fire regimes provides a unique perspective for fuels management. Although difficult to substantiate, frequent burning during the 19th century may have altered the nature of Ozark fuels by increasing herbaceous and grass vegetation, possibly leading to even lower fuel loading (for example tons/acre) than reconstructed (fig. 3). Frequent and long-term burning likely led to a transition in the dominant litter type from forest leaf litter to herbaceous grass and forb litter, which possibly resulted in increased decomposition rates and decreased total litter loading. In the southeastern Missouri Ozarks, Godsey (1988) found that both annual and periodic and annual burning of an oak-hickory forest after 36 years resulted in an increased abundance of grasses, forbs, and legumes that only comprised about 0.02 tons/acre. Additionally, Hector and others (2000) discussed the differences in decomposition between plant functional groups (legumes, grasses, herbs) and showed increasing decomposition rates with decreasing litter carbon to nitrogen ratios. The conditions conducive to high litter loading potential are most likely found where forest floors are dominated by leaf litter and have been subject to fire suppression for more than 12 years. Much of the forested area of Missouri has had no fire disturbance since the mid-20th century, which has resulted in relatively high litter loading and reduced variability in litter loading compared to the previous 200+ years.

The accumulation of organic litter on forest floors has implications for many processes which involve soils, litter invertebrates, floral diversity, hydrology, and carbon cycling. Furthermore, the effects of historically frequent fire and reduced litter, as well as current and future effects, are poorly understood. Several studies have commented on the slow recovery of endophage populations and activity following burning (Crossley and others 1998). Auten (1934) and Meier (1974) found that burned Ozark sites had significant reduction in water infiltration compared to unburned sites. Studying the same Ozark experimental burn plots, Scowcroft (1965) speculated that prolonged, frequent burning eventually led to decreased soil productivity. Frequent fire also results in decreased fuel connectivity, particularly as canopy trees are killed and inputs of litter are reduced (Miller and Urban 2000). These represent only a few of the myriad of ways that frequent fire may impact forest processes, and highlight the value of continued research into the dynamics of fire frequency and severity and the subsequent impact on organic litter accumulation.

Prescribed burning management is faced with multiple challenges in the Ozark region. Few studies have been conducted to investigate the effects of fire on multiple ecosystem components. Meanwhile, previously fire-maintained communities and species are decreasing in area and abundance, and require fire disturbance to persist. Even with relatively general information about litter decay and accumulation, decisions about forest management and prescribed burning activities are better informed. For example, successful regeneration of shortleaf pine, a species of restoration concern in the Ozarks, could be greatly enhanced through better understanding of the rate of litter accumulation, which often precludes seedling establishment. Also, burning prescriptions for areas being managed for multiple resources can be tailored to achieve an optimal level of fuel loading and desired fire behavior.

Though based on regionally specific data from the Ozarks, the litter accumulation and decay estimates presented here are generalized and do not take into account interannual variability due to variable fire effects (for example partial litter consumption), climate, litter production, litter chemistry, and other influencing factors. Despite these limitations, the approach to understanding long-term litter variability is new and applicable to other locations. Many improvements to this approach are attainable, including: the incorporation of variability in fuel accumulation and decomposition between leaf fall events; taking changing climate into account; addressing differences in species and vegetation densities; and, addressing differences in modern and historic fire conditions (for example fuel consumption, fire severity). The estimates and equations provide a context for fuels management under current conditions, facilitate a new understanding of historic fire regimes, and provide the foundation for a more refined understanding of the fuel-fire interaction.

Acknowledgments

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Estimating Fuel Bed Loadings in Masticated Areas

Sharon Hood[1] and Ros Wu[2]

***Abstract**—Masticated fuel treatments that chop small trees, shrubs, and dead woody material into smaller pieces to reduce fuel bed depth are used increasingly as a mechanical means to treat fuels. Fuel loading information is important to monitor changes in fuels. The commonly used planar intercept method however, may not correctly estimate fuel loadings because masticated fuels violate the assumption that fuel particles are round. A sampling method was developed for estimating masticated fuel bed loadings using percent cover, average depth, and bulk density in three vegetation types: Jeffrey pine-white fir, ponderosa pine-Gambel oak, and pinyon-juniper. Masticated material, duff, and litter samples were collected to determine bulk densities. Loadings were calculated as the product of bulk density and depth. Total fuel median bulk densities equaled 129 (Jeffrey pine-white fir), 128 (ponderosa pine-Gambel oak), and 226 kg/m^3 (pinyon-juniper). Correlations between loading and depth were best for the Jeffrey pine-white fir type. Bulk density was most variable in pinyon-juniper. Woody material loadings calculated from the cover-depth method were generally lower than the loadings calculated from the planar intercept method, while duff and litter loadings from the cover-depth method were higher than the loadings calculated from the vertical profile measurements on the planar-intercept transect.*

Introduction

Mechanical methods to treat fuels are used increasingly in the wildland urban interface (WUI). The goal of many of these projects is to reduce wildfire or prescribed fire intensity and spread rate through modification of surface fuels and increased canopy base heights. Masticating fuels compacts the surface fuel bed by both shredding small trees and shrubs and by chipping dead and down fuels into smaller size classes. While the mastication treatment reduces fuel bed depth, it can also result in a more continuous horizontal surface fuel layer and cause mixing of the woody material into the duff and litter layers. Because mastication is a relatively new fuels treatment, it is unclear how these treatments will affect surface fire behavior or the resulting fire effects.

Gathering fuel loading information is important for predicting fire behavior and explaining post-fire effects for any fuels treatment. However, Brown's planar intercept and duff/litter profile method (Brown 1974; Brown and others 1982) may not estimate fuel loadings accurately in masticated areas because masticated fuels are highly irregular in shape and size and may violate the assumption of round fuel pieces. In this paper, we propose the cover-depth method as an alternative to the planar intercept method when estimating masticated fuel bed loadings. For the cover-depth method, square one meter frames are placed along a fuel transect and the percent cover of the fuel bed (masticated/woody material, litter, and duff) and masticated/woody only is estimated. Depth to mineral soil is then measured and the percent that

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is masticated/woody and the percent that is litter of the vertical profile are estimated. Loadings can then be estimated by multiplying the bulk densities presented here by the fuel bed depth and cover class.

Specifically our objectives were: 1) determine bulk densities of the total fuel bed and the individual woody, litter, and duff layers, 2) test a new method to estimate fuel loadings using cover and depth (cover-depth method), and 3) compare loadings estimated from the cover-depth method and the planar intercept method in masticated areas.

Methods

Study Sites

Treatment areas were located on the San Juan National Forest in southwestern Colorado (CO) and the Lassen National Forest in northern California (CA). We chose sites on the San Juan National Forest that had pre-treatment fuels data in two vegetation types: pinyon-juniper (*Pinus edulis* Engelm. and *Juniperus osteosperma* (Torr.) Little) and ponderosa pine-Gambel oak (*Pinus ponderosa* P. & C. Lawson and *Quercus gambelii* Nutt.). There were three pinyon-juniper sites, IC, MAHN, and KRC, and three ponderosa pine-Gambel oak sites, HAYD, MLCK, and NJAK. The California site, GRAYS, was dominated by Jeffrey pine (*Pinus jeffreyi* Grev. & Balf.) and white fir (*Abies concolor* (Gord. & Glend.) Lindl. ex Hildebr.) and had no pre-treatment fuels data. It was part of a separately funded Joint Fire Science Program proposal.

Both vertical and horizontal shaft machines were employed for mechanical treatment of fuels. Vertical shaft hydro-mowers or hydro-axes were used more commonly because of superior maneuverability on steep slopes and less ground disturbance. The size and distribution of fuel pieces after a treatment was dependent on the equipment, the operator, and site conditions. No material was removed from the CO sites. The CA site was thinned from below and merchantable trees were whole tree yarded before mastication treated activity fuels and small trees and shrubs.

Field Measurements

Existing fuel transects were used to compare loadings estimated from the planar intercept method and the cover-depth method on all sites. The CA site had two transects per plot, with transects radiating from plot center at right angles to each other. The CO sites had multiple transects per plot and followed FIREMON protocols (Lutes and others 2006). All transects were established from random start locations. We placed square frames (1 m^2 area) at 5, 10, 15, 20, and 25 meters at the CA site and at 15 and 24 meters at the CO sites on each transect (fig. 1). Photographs were taken approximately one meter above each frame in order to develop a visual aid for estimating cover. Total cover of duff, litter, and woody material and only woody cover (dead and down fuels and masticated material) were estimated for each frame using FIREMON cover classes (Lutes and others 2006).

If fuels were evenly distributed throughout the frame, depth was recorded at each corner and the middle of the plot to the nearest 0.5 cm. Fuel depth was measured from the top of the masticated material to the mineral soil. We

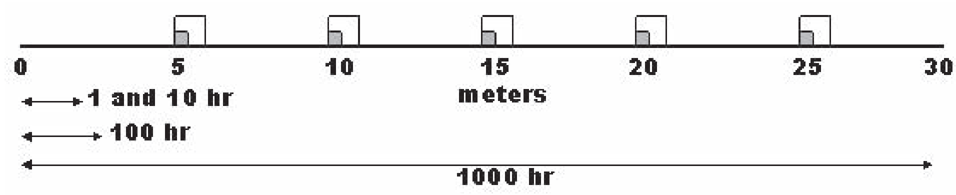

Figure 1—Example transect and frame layout of masticated fuel loading study. Each plot contained multiple transects.

estimated the percent of the vertical profile consisting of masticated/woody material and the percent litter following FIREMON methodology at each point where depth was measured. If fuel distribution inside the frame was markedly uneven, we assessed fuels by visually dividing the area into homogenous clumps. The proportion of each clump was recorded and fuel bed depth measured. We took one depth measurement for every 25 percent area the clump covered.

A 30 x 30 cm square sub-frame was placed in the lower left-hand corner of each one meter frame for collection of fuels to determine bulk density (fig. 1). If fuel bed total cover inside the sub-frame was 100 percent, depth was recorded using the same method as described for the 1 m^2 frame. Care was taken to minimize disturbance to the fuel bed while measuring depth. We did not sample the sub-frame if total cover was less than 100 percent because of the difficulty in calculating volume and bulk density. We collected all fuels inside the sub-frames with 100 percent cover to mineral soil separately by three fuel types: masticated/dead and down fuels, litter, and duff. Duff and litter were combined on the pinyon-juniper subplots because of difficulty in separating the two layers. While the fuels were generally arranged in layers, we found more mixing and compression of the woody material into the litter and duff layers than is seen on unmasticated sites. Woody material was placed into litter and duff collection bags if the particle's cross-section was in the litter or duff layer, leading to higher weights for these layers. Pieces extending outside the sub-frame were cut with clippers or a hand saw.

Dead and down woody fuels were counted along 23 m transects using the planar intercept method (Brown 1974). Masticated pieces are often irregularly shaped; therefore, diameters of the pieces were averaged for placement into a time-lag fuel size class (1, 10, 100, and 1000 hour). Duff and litter depths were recorded at 14.5 m and 24 m along each transect.

Data Analysis

Fuel bed samples from the sub-frames were dried at 105°C for 48 hours or until sample weight stabilized and then weighed to the nearest gram. Total fuel bed volume and individual fuel bed component volume was calculated by multiplying dimensions of the sub-frame by the average depth of the vertical profile. Bulk density of each sample was then calculated by dividing the oven-dry weight of the sample by the volume. Because of the mixing and compression of fuel bed layers and difficulty in separating the layers during collection, we feel it is more accurate to use the total subplot sample weight and the individual fuel component depth to calculate loadings and bulk densities.

Fuel bed loading was determined by multiplying the median bulk density of each vegetation type by the average depths of the one meter frames as if cover was 100 percent. The loadings were then reduced based on recorded cover class and clumping proportions. Loadings were calculated individually by fuel bed component and together. The total bulk density and loadings were calculated using average total depths and summed masticated, duff, and litter weights. All loadings reported here were calculated using the median total fuel bed bulk density and individual fuel bed component depth.

We also developed linear regression equations by vegetation type to estimate loadings using fuel bed depth as the independent variable (SAS Institute Inc. v 9.1). If the intercept was not significant (*p-value* ≥ 0.05), it was dropped from the regression equation.

Five sub-samples of duff and litter from each vegetation type were randomly selected to determine mineral ash content because of potentially higher mineral soil contents in the fuel bed from the mixing and compression of layers during mastication. Higher mineral soil content increases bulk densities. The samples were placed in a muffle furnace at 450°C for 24 hours to combust all organic matter. The mineral ash content (percent) was calculated by dividing the weight of the mineral ash by the weight of the oven-dried sample.

Loadings were also calculated from data collected using the planar intercept/duff-litter profile method. We used the FIREMON v. 2.1.2 software to calculate these fuel loadings (Lutes and others 2006). All frame loadings and transects loadings were averaged by vegetation type and site to determine average site loadings.

Results and Discussion

We collected 17, 41, and 26 sub-frame (30 x 30 cm) samples on 3, 17, and 13 plots in the Jeffrey pine-white fir, ponderosa pine-oak, and pinyon-juniper vegetation types, respectively. Fuel bed depth was highest on the Jeffrey pine-white fir site and lowest on the Pinyon-Juniper sites (fig. 2). The masticated layer averaged approximately 3.0 cm for all vegetation types.

Average litter mineral ash content was 3.9 percent in the Jeffrey pine-white fir, 11.2 percent in the ponderosa pine-oak, and 26.2 percent in the pinyon-juniper (includes duff). Average mineral content of the duff samples were high. We found 32.4 and 42.4 percent mineral content for Jeffrey pine-white fir and ponderosa pine-oak, respectively. The high mineral content for the pinyon-juniper litter samples was probably a result of combining the duff and litter into one sample bag during collection. The pinyon-juniper sites also have a much higher percentage of bare soil than the other vegetation types which may have resulted in mixing of bare soil into the duff and litter material when the mastication treatment was applied.

Median fuel bed bulk density was very similar for Jeffrey pine-white fir and ponderosa pine-oak (129 and 128 kg m^{-3}), but pinyon-juniper bulk density was much higher (226 kg m^{-3}) (fig. 3a). Median bulk density of the masticated/woody layer only was 155, 136, and 218 kg m^{-3} for Jeffrey pine-white fir, ponderosa pine-oak, and pinyon-juniper, respectively (fig. 3b). Variability decreased when litter, duff, and woody material samples were combined into one forest floor sample per plot to calculate bulk densities (fig.3). This was likely due to the difficulty of accurately separating the individual fuel components during collection.

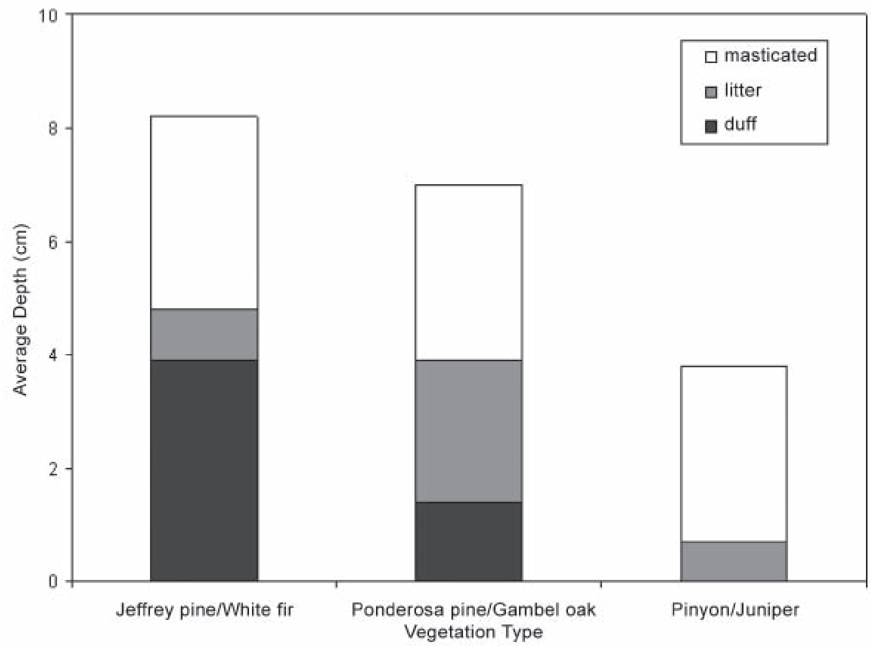

Figure 2—Average depth of surface fuels and forest floor by vegetation and fuel type.

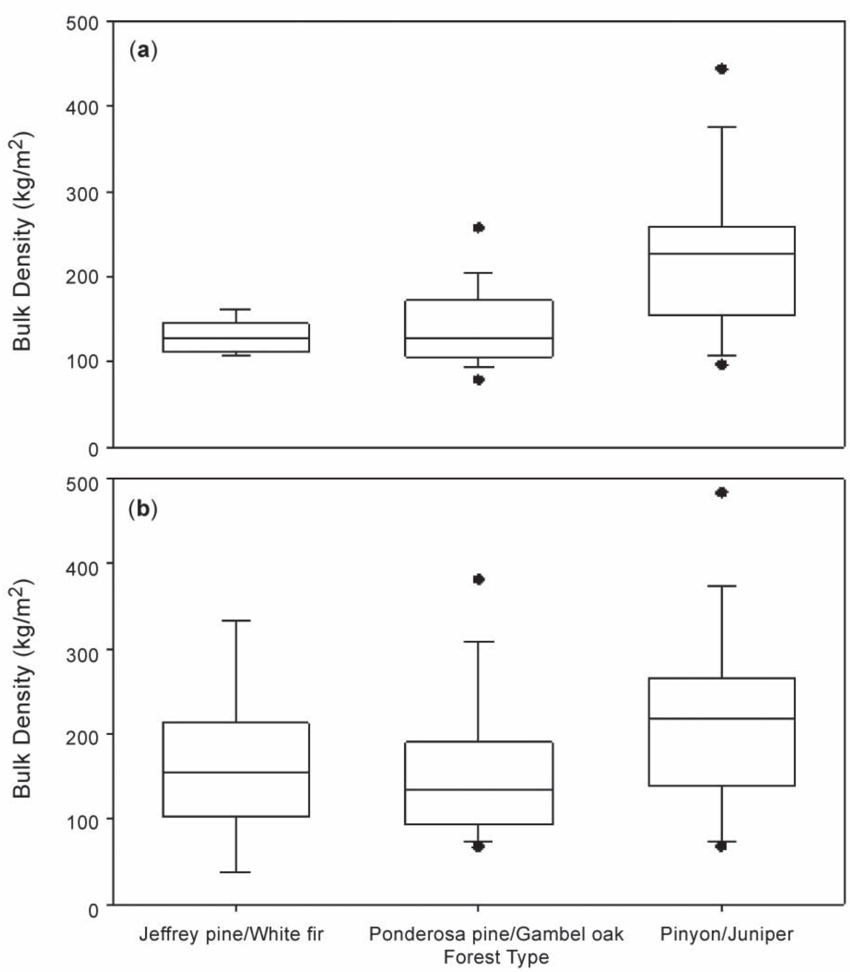

Figure 3—Bulk density of (a) total surface and forest floor fuel loadings and (b) only surface masticated and woody fuel loadings in subplots by vegetation type. Solid lines represent median values. Dots are 5th and 95th percentile outliers.

Total fuel bed loadings calculated from the sub-frames where cover was 100 percent were highest in the Jeffrey pine-white fir type (9.6 kg m^{-2} (42.8 tons/acre)), followed by ponderosa pine-oak (8.2 kg m^{-2} (36.6 tons/acre)) and pinyon-juniper (7.3 kg m^{-2} (32.6 tons/acre)). Average masticated/woody fuel loadings were highest in the pinyon-juniper plots (5.6 kg m^{-2} (25.0 tons/acre)). Masticated loadings in the Jeffrey pine-white fir and ponderosa pine-Gambel oak plots were similar (4.0 and 3.9 kg m^{-2} (17.8 and 17.4 tons/acre)). Loadings increased generally linearly with depth. Variability was high except for the Jeffrey pine-white fir type (fig. 4). The intercept was non-significant for only the Jeffrey pine-white fir type. Regressions equations for estimating total loadings are given in figure 4.

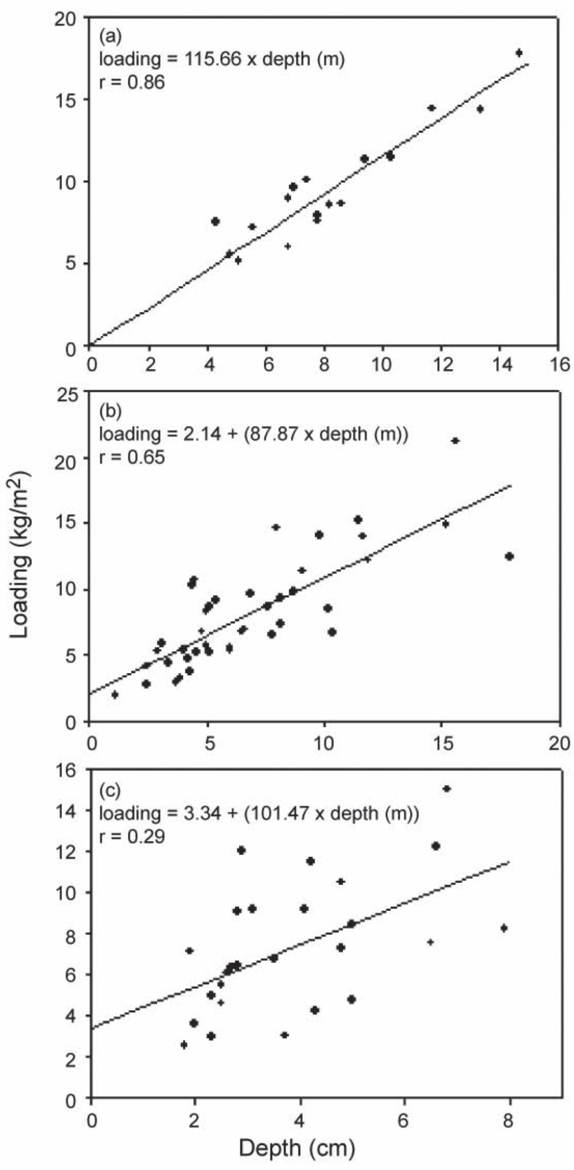

Figure 4—Regression showing relationship of total fuel bed depth and loading for samples in (a) Jeffrey pine-white fir, (b) ponderosa pine-Gambel oak, and (c) pinyon-juniper vegetation types.

Woody fuel loadings estimated with the cover-depth method were usually lower (fig. 5a) and duff and litter loadings higher (fig. 5b) than the loadings estimated with the planar intercept method. The difference between the two methods can be attributed to both differences in average depths and bulk densities. The cover-depth method requires more depth measurements (5 per 1 m^2 per frame) than the planar intercept method (2 per transect). The duff and litter bulk densities calculated from the 30 x 30 cm sub-frames were higher than the ones used by FIREMON to calculate loadings (44 kg m^{-3} for litter and 106 kg m^{-3} for duff), especially for the pinyon-juniper vegetation type.

The Jeffrey pine-white fir vegetation type had the strongest correlation between loading and depth. This could be due to more uniform stand conditions than the ponderosa pine-Gambel oak and pinyon-juniper types, both inherently and from treatment application. Also, all data collected in the Jeffrey pine-white fir type came from one site, whereas data for the other vegetation types were collected across several sites. The pinyon-juniper type was the most variable type and had the highest bulk density.

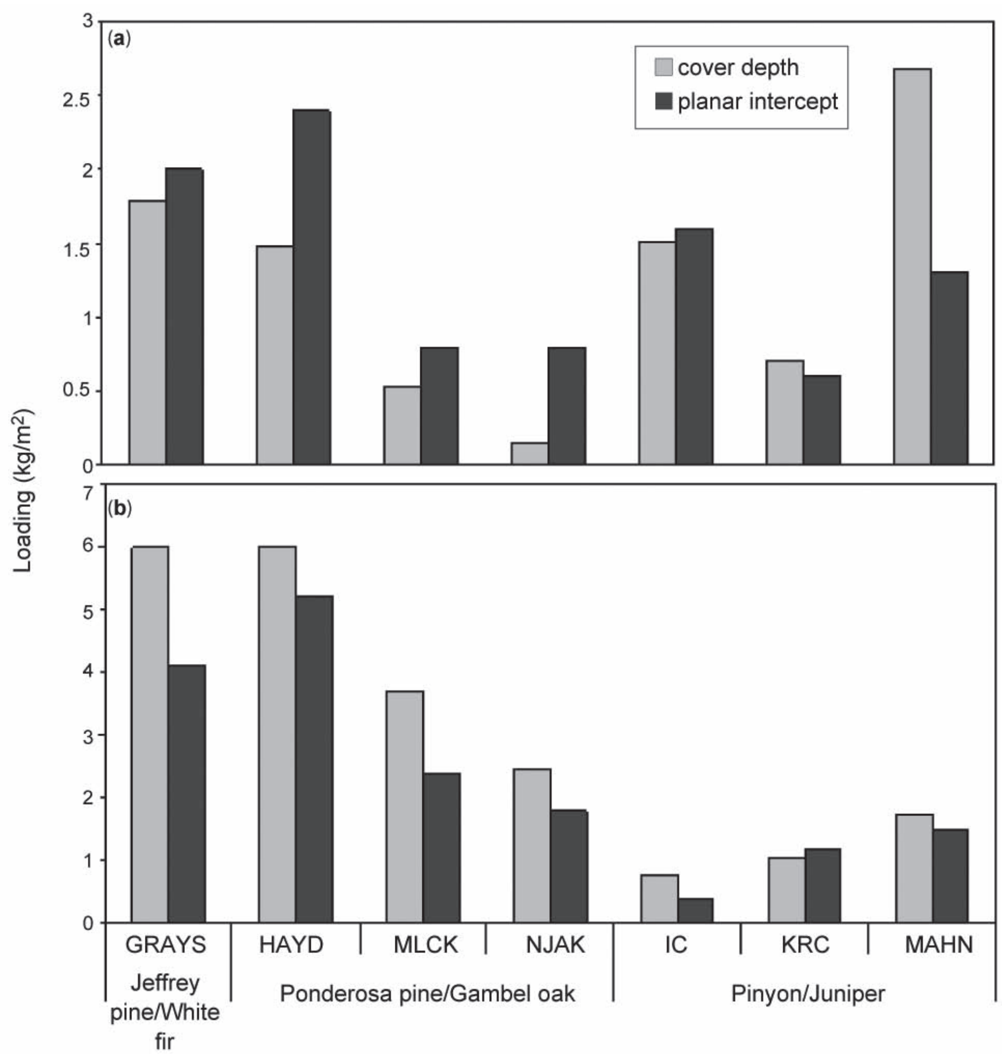

Figure 5—(a) Masticated and down woody and (b) litter and duff fuel loading estimations using the cover-depth method and Brown's planar intercept/duff-litter profile method.

The cover-depth method estimated higher duff and litter loadings and lower woody fuel loadings than the planar intercept method for most sites. Our next step is to perform an accuracy assessment based on the data collected in the sub-frames to determine which method is better for estimating fuel bed loadings in masticated areas. We also plan to assess if fewer depth measurements would produce similar results, thereby speeding the data collection process. If the cover-depth method proves to more accurately estimate loadings than the planar intercept method, more sampling in more vegetation types will be necessary to completely test this method.

Aknowledgements

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Variability in Loading of Mechanically Masticated Fuel Beds in Northern California and Southwestern Oregon

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***Abstract**—The use of mechanical mastication to treat non-merchantable fuels is becoming increasingly popular, but loadings and other characteristics of masticated fuel beds are unknown. Surveys of eight recently masticated sites in northern California and southwestern Oregon indicate that significant site level differences were detected for 1 hr and 10 hr time-lag classes and total woody fuel loading ($P < 0.0001$). The majority of the total woody fuel loading occurred in the 10 hr time-lag class (76.9 ± 14.1 percent) at all 10 sites. At one particular site, planar intercept estimates of woody fuel loading were 181.7 (± 20.3) % higher than estimates using a plot-based method. When the actual average squared quadratic mean diameter values (1 hr = 0.06 cm^2, 10 hr = 1.09 cm^2 and 100 hr = 11.8 cm^2) were used, woody fuel loading estimates between the two methods did not differ statistically. Across sites, fuel depth was not a significant predictor of fuel loading ($R^2 = 0.24$, $P = 0.22$). However, a significant relationship between fuel depth and loading was found at the individual site level, except for one site (WFR). Species masticated, mastication machinery used, and operator experience are some of the potential reasons why the depth to loading relationship differed among sites.*

Introduction

In the foothill and montane regions of northern California and southwestern Oregon, the combination of weather and fuel conditions has led to many recent catastrophic wildfires (e.g., Fountain, Jones and Biscuit fires). These events are a deviation from the historical fire regime of relatively frequent, low to moderate intensity fires of this region (Skinner and Chang 1996, Taylor and Skinner 2003). Due to the successful fire suppression over the last century (Agee 1993), wildfire size and intensity has increased, bringing national attention to fire management and policy. Public awareness is especially pronounced in residential communities located within or adjacent to areas of elevated fuel accumulation. Solutions to reduce the risk of wildfire in these areas have often resorted to the use of mechanical fuel treatments.

One method of mechanically treating non-merchantable fuels that has become increasingly popular in the western United States is mastication. Mastication is the process of converting live or dead standing biomass into surface fuel by "chewing" or breaking up larger pieces into smaller portions by the means of a front-end or boom-mounted rotary blade or head (fig. 1). In northern California and southwestern Oregon, mastication equipment is primarily used to treat shrub and small tree fuels, typically along fuel breaks and within the wildland-urban interface. Machinery used to masticate woody fuels is highly varied but have similar mechanical treatment properties.

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Figure 1—General masticator types: front-end mounted, Takeuchi®,TL150 w/ FECON Bull hog®shredder head (left) and a boom-mounted FECON Bull hog® shredder head mounted on an excavator (right). (left-Photo courtesy of Nancy Curran, USDA Forest Service).

Mastication results in the translocation of typically living shrub and midstory fuel beds, thereby increasing dead surface woody fuel loading (fig. 2). The reduction of potential ladder fuels and compaction of surface fuels as a result of mastication are appealing to land managers and have contributed to the dramatic increase in its use.

While the popularity of mastication to treat fuels is increasing, little work has been conducted to quantify and characterize the variability in masticated fuel beds. This lack of information is an important shortcoming to installing subsequent fuel treatments and an impediment to modeling potential fire behavior and effects in treated areas. In order to provide land managers with appropriate information regarding the use of mastication and subsequent fire behavior and effects, research accurately quantifying and characterizing masticated fuel beds is necessary.

Figure 2—Mad River (MAD) masticated site contrasting untreated shrub fuels in the background with treated dead woody fuels in the foreground.

The purpose of this study was to provide preliminary analyses characterizing the variability among masticated sites in northern California and southwestern Oregon as part of a larger study that aims to create custom fuels models for masticated fuel beds. Specifically, the objectives of this paper were to:

1) Quantify site level variability in masticated fuel bed loading
2) Compare and contrast methods of estimating fuel loading in masticated areas
3) Determine if fuel bed depth is significantly related to total woody fuel loading

Methods

Study Sites

Throughout northern California and southwestern Oregon, eight study sites were selected to investigate variability in loading of masticated fuel beds. Study sites were located primarily on federal land (USFS, BLM and NPS), with one site on a private forest (Whitmore). The vegetation masticated within each of the study sites varied but was predominantly shrub (*Arctostaphylos* spp., *Ceanothus* spp.) and/or small hardwood tree species (*Lithocarpus densiflorus*, *Arbutus menziesii*). All mastication treatments were completed using either a front-end or boom-mounted masticator, and all mastication was conducted between November 2002 and May 2005 (table 1).

Field Sampling

Surface fuel loading was calculated for each study site using two methods: the planar intercept (Brown's transect) method (Brown 1974) and a plot-based sampling method. At each study site, long baseline transects traversing the treated areas were placed at random azimuths. At 25 m increments along these baseline transects, a Browns transect was established at a random azimuth. Brown's transect lengths were typically 20 m but occasionally less when the transect neared the edge of a treated area. At each Brown's transect, 1 hr

Table 1—Site names, locations, date of mastication and masticator type for all masticated study sites in northern California and southwestern Oregon, U.S.A. (BM= boom-mounted, FE = front-end mounted).

Site Code	Site Name	Location	Mastication Date	Masticator Type
APP	Applegate Valley	Applegate Valley, Oregon (BLM)	Apr./May 2005	BM-Slashbuster® brush cutter
CFR	Challenge Fuel Reduction	Plumas National Forest, California (USFS)	Dec. 2002 Mar. 2003	BM-Slashbuster® mounted on an excavator
IMR	Iron Mountain Rd.	Redding, California (BLM)	Nov. 2004	FE-Masticating head on an ASV Positrack™
MAD	Mad River	Six Rivers National Forest, California (USFS)	Dec. 2004	FE-Takeuchi®,TL150 w/ FECON Bull hog® shredder head
SFR	Sierraville Fuel Reduction	Tahoe National Forest, California (USFS)	May/June 2003	FE-Rayco® Forestry Mower (small) on a bulldozer
TAY	Taylor Ridge	Klamath National Forest, California (USFS)	Apr./May 2005	BM-“Brontosaurus” head on excavator
WFR	Whitmore Fuel Reduction	Whitmore, California (Private)	May 2003	FE-Rayco® Forestry Mower (small) on a bulldozer
WHI	Whiskeytown	Whiskeytown NRA (NPS) California	Nov. 2002	FE-Slashbuster® on an ASV Positrack™

(0.0-0.6 cm-diameter) and 10 hr (0.6-2.54 cm-diameter) time-lag fuel size classes were tallied along the first 2 m, while 100 hr (2.54-7.6 cm) fuel particles were tallied along the first 4 m. The entire transect length was surveyed for 1000 hr (>7.6 cm) fuel particles and their actual diameters were measured, species recorded, and decomposition category (sound or rotten) assigned. Since masticated fuel particles are often irregularly shaped, determination of the size class of each particle was made along the narrowest diameter that intersected the planar transect. Fuel bed depth measurements were made at three points along the transect (5 m, 10 m, and 15 m).

For the plot-based sampling method, a 50 cm x 50 cm metal frame was placed at the 7 m mark along the planar intercept transect. All woody fuels inside the frame were collected; in the event that a woody fuel particle crossed the frame, the piece was cut along the boundary and the interior portion was retained. To characterize fuel bed bulk density, four large pins were placed 10 cm from each of the frame corners. At each pin, fuel bed depth was measured by progressive removal of each fuel layer. All woody fuels were separated in the lab by time-lag classes and then oven-dried for at least 72 hrs at 75 °C in a mechanical convection oven and then weighed on an analytical balance.

At the Mad River (MAD) mastication site, loading estimates for woody fuels were calculated using the composite squared average quadratic mean diameter values for each fuel size class (1 hr = 0.08 cm^2, 10 hr = 1.3 cm^2, 100 hr = 11.9 cm^2) provided by Brown (1974). In addition, woody fuel loading was calculated using actual squared average quadratic mean diameter values (1 hr = 0.06 cm^2, 10 hr = 1.09 cm^2 and 100 hr = 11.8 cm^2) determined from collected fuels. Fuel quadratic mean diameters were generated by measuring the average of the minimum and maximum squared diameters for a subsample of fuel particle collected with the plot sampling method (1 hr, n = 1187; 10 hr, n = 170; 100 hr, n = 4).

Data Analysis

Means and standard errors were calculated for site-level estimates of total fuel loading and loading of different time-lag classes for both the planar intercept and the plot-based sampling methods. A one-way analysis of variance (ANOVA) was conducted to detect a site level effect for mean total woody fuel loading and mean loading by time-lag classes. If differences were detected, a post-hoc Bonferoni means comparison test was used to detect significant differences among sites (Sokal and Rohlf 1995). Linear regression analysis was used to determine the relationship between total woody fuel loading calculations and fuel bed depth across all sites and at the individual site level. All statistical tests were computed using STATA (Statacorp 2005) and statistical significance was based on an $\alpha = 0.05$.

Results

Site Level Variation

For estimates made using the plot-based method, sites differed significantly in total woody fuel loading and loading by 1 hr and 10 hr time-lag classes ($P < 0.001$; table 2). The MAD site had the highest total woody fuel loading (63.4 Mg ha^{-1}) and contained more 10 hr fuel loading than all sites except Applegate Valley (APP) and Taylor Ridge (TAY; fig. 3). The

Table 2—Plot based sampling method estimates of mean fuel loading (± standard error) of woody fuel classes and fuel height for masticated sites in northern California and southwestern Oregon.

		Plot-based sampling method					
Site	**n**	**1 hr**	**10 hr**	**100 hr**	**1000 hr**	**Total Woody**	**Fuel Depth**
		- - - - - - - - - - - - - - - - - - (*Mg ha^{-1}*) - - - - - - - - - - - - - - - - - -					(*cm*)
APP	15	12.3 (2.8)	24.6 (4.3)	8.6 (4.8)	5.3 (5.3)	50.7 (9.9)	6.9 (0.7)
CFR	40	8.1 (0.7)	19.2 (1.6)	7.9 (1.7)	3.5 (2.2)	38.7 (7.2)	N/A
IMR	15	6.2 (1.7)	13.8 (2.5)	3.6 (1.7)	0.0 (0.0)	23.6 (6.9)	4.9 (0.8)
MAD	15	23.5 (2.6)	34.8 (2.6)	5.1 (2.5)	0.0 (0.0)	63.4 (7.8)	4.6 (0.8)
SFR	15	5.2 (1.0)	11.1 (1.4)	6.6 (2.9)	0.0 (0.0)	22.9 (5.4)	3.2 (0.5)
TAY	15	13.2 (2.9)	21.7 (2.7)	2.1 (0.8)	0.0 (0.0)	37.0 (6.4)	5.0 (0.5)
WFR	40	4.4 (0.7)	9.4 (1.7)	1.6 (0.6)	0.0 (0.0)	15.3 (2.8)	4.4 (0.6)
WHI	15	11.8 (2.4)	16.4 (1.8)	3.6 (1.5)	0.0 (0.0)	31.8 (5.2)	5.8 (0.3)
All Sites		10.6 (2.2)	18.9 (2.9)	4.9 (0.9)	1.1 (2.8)	35.4 (2.8)	4.9 (0.6)

Whitmore fuel reduction (WFR) site had the lowest total woody fuel loading (15.3 Mg ha^{-1}) and contained significantly less in 10-hr fuel loading than all other masticated sites (fig. 3). Post-mastication fuel loading was concentrated in the 10-hr and 100-hr time-lag classes, which made up 76.9 (± 14.1) percent and 11.5 (± 5.8) percent of the total woody fuel load, respectively. Loading of 10-hr time-lag class was approximately 250-300 percent greater in some sites (e.g., MAD, APP) than others (e.g., SFR, WFR).

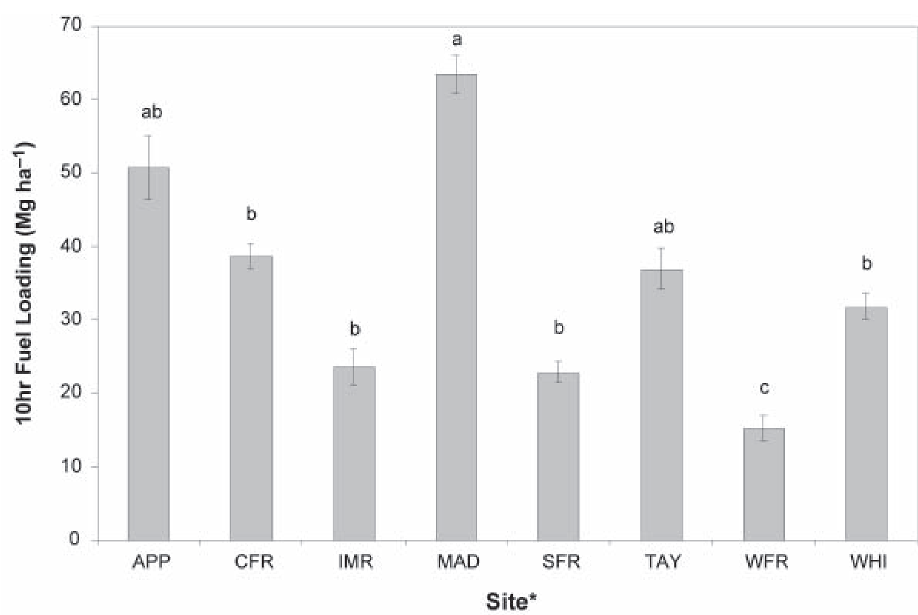

Figure 3—Ten-hour fuel loading in masticated sites in northern California and southwestern Oregon across all sites from the plot-based method estimates (letters above error bars denote significant difference between sites using Bonferoni means comparison test).* = full site names provided in table 1.

Fuel Load Methods Comparison

At the MAD site, total woody fuel estimates using the Brown's planar intercept method with the composite squared average quadratic mean diameter values given by Brown (1974) were 180.5 (± 55.4) percent higher than the estimates made using the plot-based sampling method. Preliminary results from the MAD site suggest that the actual average quadratic mean diameters of masticated particles are smaller than the composite values given in Brown's formula (1974). When the actual quadratic mean diameter measures at the MAD site were used in the fuel loading calculations, the total loading values no longer differed from those estimated using the plot-based method (fig. 4). Even though the total fuel loading did not differ, Brown's transect values were substantially greater than the plot-based sample values for 10-hr fuels and substantially less than the plot-based sample values for 1-hr fuels (fig. 4).

Predictors of Total Woody Fuel Loading

Land managers and researchers are often interested in simplifying measures of fuel loading to improve cost effectiveness and sampling efficiency. Fuel depth is a measure that is often sought to correlate with total woody fuel loading. Average fuel depth values for masticated sites ranged from 3.0 to 6.9 cm. Based on linear regression analysis, fuel depth and total woody fuel loading over all study sites were not related ($P = 0.22$, $R^2 = 0.24$). However, within sites, a significant relationship between depth and woody fuel loading

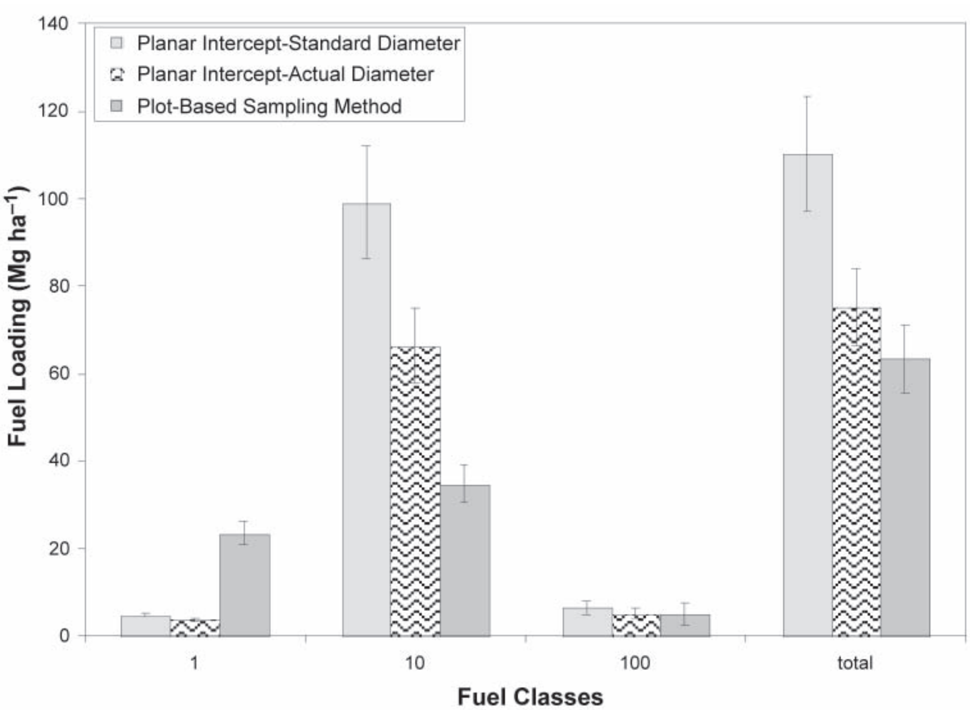

Figure 4—Total woody fuel loading comparisons of the planar intercept method with standard calculation of quadratic mean diameter, planar intercept method with actual quadratic mean diameter and estimates from the plot-based sampling method for the MAD mastication site.

was found at all except the WFR site ($R^2 = 0.03$, $P = 0.28$). The MAD site had the strongest relationship between depth, and woody fuel loading of all sites ($R^2 = 0.84$), while the R^2 values of other sites ranged from 0.24 to 0.74. Equations are still being developed and are not shown here.

Discussion

Variation in woody fuel loading has many implications for both fire behavior and effects. The results of this study suggest that large variations in woody fuel loading exist across 1-hr and 10-hr time-lag classes within masticated areas of northern California and southwestern Oregon. Site level differences in total woody fuel loading found in this study were largely driven by the MAD and WFR sites, which had both the highest and lowest fuel loading in the 10-hr time-lag class, respectively (fig. 3). Variation in woody fuel loading of masticated sites in our study suggests that different fuel models may be necessary to accurately assess fire behavior and effects in these areas.

Site level variation in total woody fuel loading across all time-lag fuel classes for masticated sites was not entirely unexpected. Primary sources of variation in masticated fuel beds may be linked to pretreatment biomass and time since mastication, although secondary factors such as decomposition rate and time since disturbance may be important in determining total woody fuel loading. Masticator type, mastication intensity, and the size and/or age of treated fuels are likely contributors to variation in the proportion of fuels in different time-lag classes.

Independent of the variability found in loading, fine fuel particles (particularly 10 hr) were the dominant woody fuel across all sites. These findings have broader implications, suggesting that in spite of the many different types of masticators used and the level of variability in loading, there are consistent trends in the size of the fuel particles produced by mastication. The presence and quantity of fine fuel particles are well-known to influence fire behavior (Rothermel 1983) and may strongly influence fire effects in masticated areas.

When actual quadratic mean diameter measurements of masticated particles were used in the planar intercept fuel loading calculations, the two methods produced similar estimates of fuel loading. However, the planar intercept method underestimated 1-hr fuel loading while simultaneously overestimating 10-hr fuel loading. An explanation for this inconsistency may be due to the fact that the Brown's transect estimates were made in the field after significant fall rains, while the material collected with the plot-based method was dried in an oven prior to sorting into size categories. Prolonged drying of fuels may have caused a reduction in particle diameter, with 10-hr fuels in the field becoming 1-hr fuels in the lab. Since fires occur when the fuels are dry, the numbers obtained with the plot-based method have greater applicability to fire behavior and fire effects modeling. Results to date suggest that either method can be used to estimate total woody fuel loading (especially if the fuels are dry), but that squared averaged quadratic mean diameters specific to masticated fuels should be used in calculations with the planar intercept method. So far we have only made measurements of fuel particle size at one site and additional measurements are being made to determine if average particle size differs among sites.

While the plot-based sampling method appears to be useful for estimating loading of masticated fuels, several disadvantages exist. The plot-based method is time intensive and therefore, more costly and doesn't evaluate enough area to appropriately account for relatively uncommon 1000 hr fuels, compared to the planar intercept method.

Fuel depth was not found to be a significant predictor of total woody fuel loading possibly because of differences among sites caused by masticator type, operator experience, mastication effort, and vegetation type. It may therefore, not be feasible to create a universal equation relating depth to loading for this type of masticated fuel. While a relationship across all sites was not observed, all but one site's total woody fuel loading was significantly related to fuel depth. Relationships between fuel depth and woody loading may aid in determining simpler and faster means to calculating woody fuel loading within masticated sites. Surrogate measures of total woody fuel loading have been established for other areas (Fulé and Covington 1994) and deserve further investigation in masticated fuel beds.

The quantification and characterization of fuel loading in masticated sites have ramifications for the prediction of fire behavior and effects. Managers and researchers (Bradley and others 2006; Knapp, personal observation) report a high degree of variability in fire behavior with prescribed burning in masticated fuels, which may partially be related to variations in fuel loading. Differences in loading have additionally been shown to influence depth and duration of lethal soil temperatures during burning (Busse and others 2005). In spite of the growing popularity and use of mastication, many unknown factors still exist in characterizing this novel fuel type. The level of variation encountered within our study suggests that several custom fuel models may be necessary to adequately predict fire behavior and effects. Additional work to determine if differences in average particle size exist among sites, how these differences relate to site parameters, and the extent to which mastication alters the surface area to volume ratio of fuel particles, is in progress.

Acknowledgments

These preliminary results are a part of a larger study investigating the development of custom models for masticated fuel beds. Funding for this project was provided by the Joint Fire Science Program. Earlier drafts of this report were improved with the help of Emily Orling. This project was greatly advanced by Elishau Dotson and Emily Orling, who assisted with field data collection.

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Creating a Fuels Baseline and Establishing Fire Frequency Relationships to Develop a Landscape Management Strategy at the Savannah River Site

Bernard R. Parresol[1], Dan Shea[2], and Roger Ottmar[3]

Abstract—*The Savannah River Site is a Department of Energy Nuclear Defense Facility and a National Environmental Research Park located in the upper coastal plain of South Carolina. Prescribed burning is conducted on 15,000 to 20,000 ac annually. We modified standard forest inventory methods to incorporate a complete assessment of fuel components on 622 plots, assessing coarse woody debris, ladder fuels, and the litter and duff layers. Because of deficiencies in south-wide data on litter-duff bulk densities, which are the fuels most often consumed in prescribed fires, we developed new bulk density relationships. Total surface fuel loading across the landscape ranged from 0.8 to 48.7 tons/ac. The variables basal area, stand age, and site index were important in accounting for variability in ladder fuel, coarse woody debris, and litter-duff for pine types. For a given pine stand condition, litter-duff loading decreased in direct proportion to the number of burns in the preceding thirty years. Ladder fuels for loblolly and longleaf increased in direct proportion to the years since the last prescribed burn. The pattern of fuel loading on the SRS reflects stand dynamics, stand management and fire management. It is suggested that the Forest Inventory and Analysis Program can easily modify sampling protocols to incorporate collection of fuels data.*

Introduction

The Savannah River Site (SRS) is a 198,344 ac land base controlled by the Department of Energy. The SRS is a Nuclear Defense Facility and a National Environmental Research Park. The SRS is located on the Upper Coastal Plain and Sandhills physiographic provinces, south of the city of Aiken, South Carolina (figure 1). Created in 1951, the SRS today contains approximately 182,420 ac of forested landscape divided into 6,009 stands across six expansive management areas.

When the SRS was established, approximately 80,000 acres were in old-fields and the balance consisted of cut over forest land with low stocking (Kilgo and Blake 2005). The planting of the old fields and cutover forests with (non-native) slash pine (*Pinus echinata*), loblolly pine (*P. taeda*) and longleaf pine (*P. palustris*) created a large block in a narrow age class and a dynamic fuel loading problem. Approximately 14 wildfires, primarily surface fires, occur each year. An effective prescribed burning program was not initiated until the mid 1970's. Today prescribed burning is conducted on 15,000 to 20,000 acres annually to reduce fire hazards and to enhance ecological communities associated with longleaf fire savannas. The SRS has also utilized herbicides to reduce mid-story vegetation, primarily for management of the endangered

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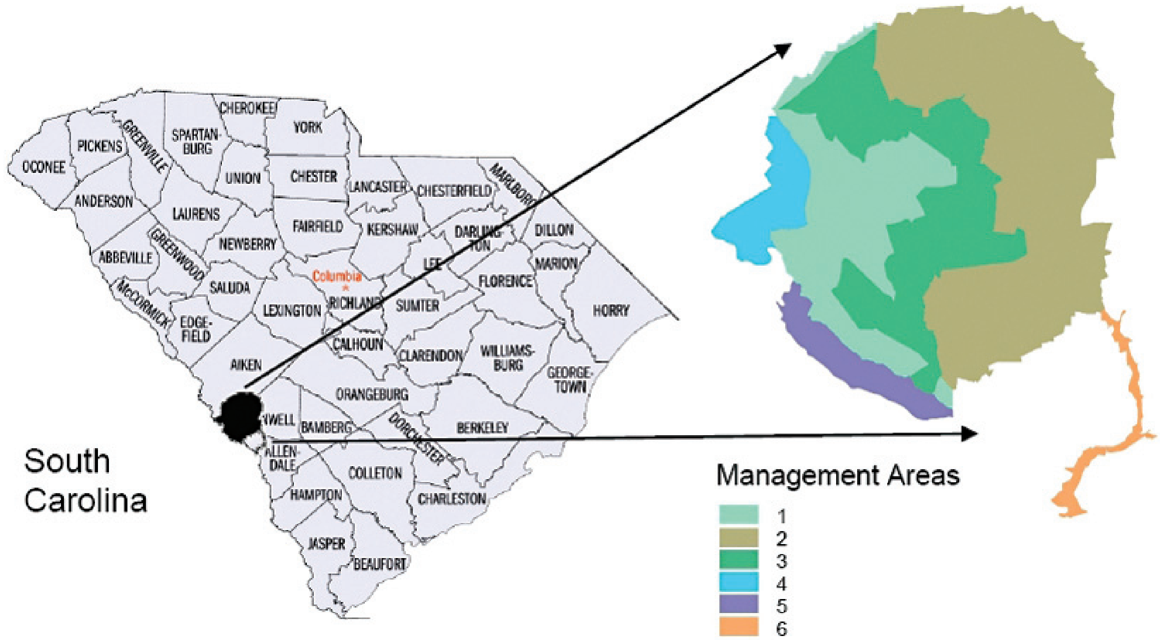


Figure 1—Location of the Savannah River Site in Aiken, Barnwell, and Allendale counties, South Carolina. The six expansive management areas are shown.

red cockaded woodpecker (*Picoides borealis*), and mechanical shredding. More recently sub-merchantable woody fuels are being considered as a fuel supply for a bioenergy fired power facility on-site. However, prescribed burning is the most cost effective technique on per acre basis. Because of smoke management constraints, which limits prescribed burning and the high costs of alternative fuel treatments, there was an identified need to optimize fuels management, including the types of stands to be treated, their location on the landscape, and the frequency of treatment.

The Need for Fuels Inventory

There are currently no periodic regional or national fuels inventories being conducted. The lack of periodic field inventories makes it impossible to gauge the effectiveness of national, regional or local fuels and fire management policies and strategies. Remote sensing methods are largely unable to accurately estimate surface fuels (Keane and others 2000) that are the main contributors to fire behavior in the South. Because of the identified need to optimize fuels management at the Savannah River Site, the periodic inventories conducted on-site were modified to include measurement of forest floor fuel variables. Small mid-story trees that contribute to ladder fuel were being captured by the existing design. Our objective was to establish a fuel loading baseline as a function of stand variables as a reference for Site management, to allocate fuel treatment strategies, and to estimate the prescribed burning frequency needed to achieve wildfire behavior objectives.

Inventory Design and Fuels Sampling

A systematic layout of sample points was installed using an approximate 1000- by 1000-meter grid over the entire SRS land base, except for the narrow corridor along the Lower Three Runs Creek that extends from the southeast boundary to the Savannah River. This resulted in approximately one sample plot per every 250 acres of the SRS, or 773 plot locations. This plot density is high from the traditional inventory perspective. Of the 773 plots, only 657 fell on forested areas. An additional data source of 62 plots that fall on the SRS from the Forest Inventory and Analysis (FIA) regional inventory (conducted by the USDA Forest Service) are included in the plot database. Combining the 62 regional inventory plots that fall on the SRS with the 657 new SRS plots produces a potential sample of 719 points (figure 2).

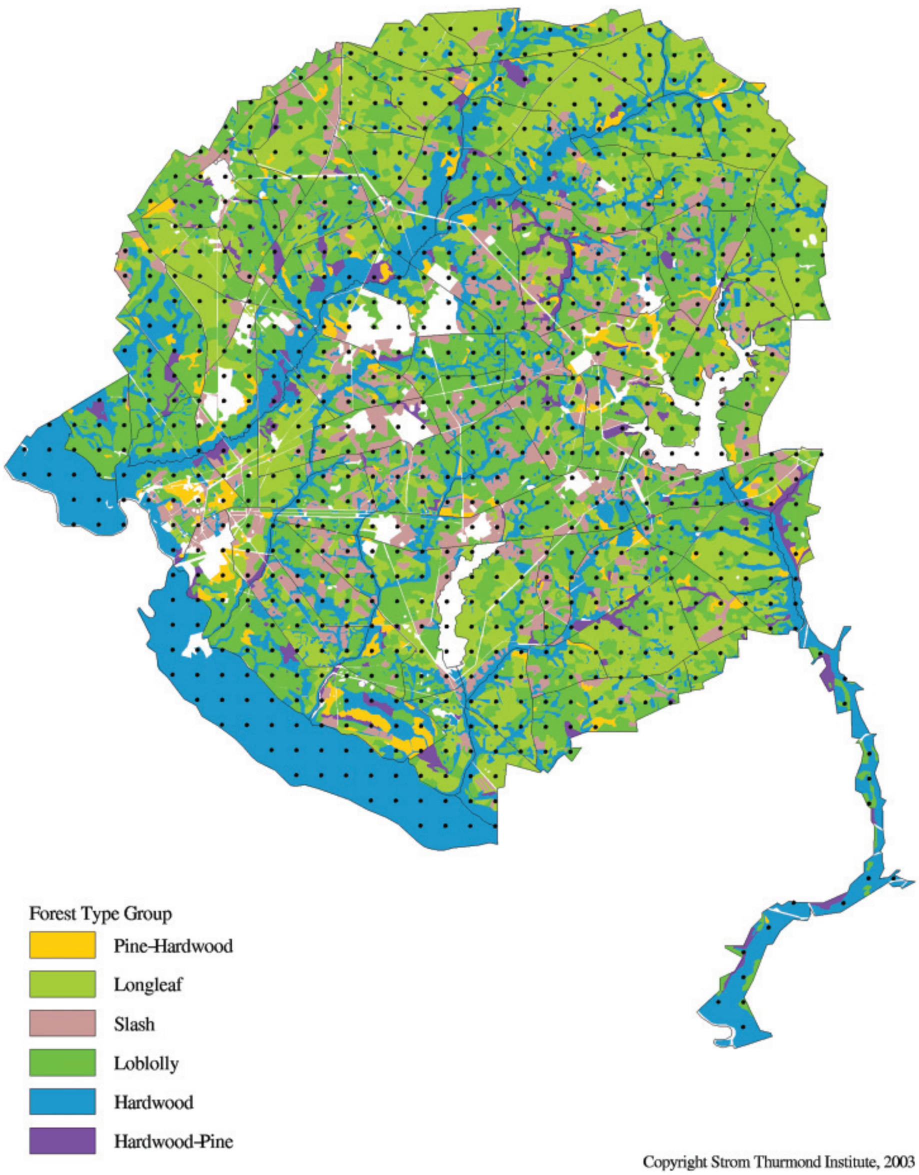


Figure 2—Systematic layout of inventory plots on the Savannah River Site and spatial distribution of the broad forest type groups.

The plot design used is a standard FIA design commonly used in the southeastern U.S. It consists of a cluster of five subplots, 70 feet between points, which are normally laid out in the scheme shown in figure 3. Two nested plot-types are established at each of these five subplot center points. One of these plot-types is a variable-radius plot using a 37.5-factor angle prism for sampling trees that are 5-inches or larger in diameter at breast height (dbh). Nested at the same point is a circular fixed-radius 1/300th-acre plot for sampling trees from 1- to 5-inches in diameter. All sampled trees from the five subplots are combined, meaning that the operative prism factor for the sample location (that is, the 5 subplots) is 7.5, and the cumulative area of the fixed-radius plots is 1/60th of an acre. The pattern shown in figure 3 is the standard subplot layout, but the arrangement was altered when necessary to insure that all subplots fall within the same stand or forest condition found at subplot 1. It was necessary to alter this arrangement in about a third of the plots on the SRS. Subplot 1 is never moved from the initially selected point location. Rotation only occurs on subplot 2 to 5, for the purpose of matching their forest condition with that of subplot 1.

In-between the five subplots are four planar transects used for measuring coarse woody debris (CWD) forest floor fuel (figure 4). These measurements are on dead woody material that has separated from the plant (trees and shrubs) that produced it, or from main stems of dead trees that have fallen down. The method for measuring CWD uses a vertical-plane-intersect plot that either counts by size class for smaller material or measures the individual diameters for diameters greater than 3 inches the pieces of CWD material that break the plot plane (Brown 1974). As shown in figure 4, counts were made along a 10-foot section of the transect line of dead downed material with diameters of 0-0.25 inches (1-hour fuels). Counts of pieces with diameters in the 0.25-1.0 inch range (10-hour fuels) were made at the same time along the same 10-foot section of the transect line. Counts were made of pieces with diameters of 1.0-3.0 inches (100-hour fuels) along a 20-foot transect. Dead downed material larger than 3 inches diameter encountered along the full 70-foot transect had their individual diameters at the point of intersection measured, and their condition was classed as either solid or

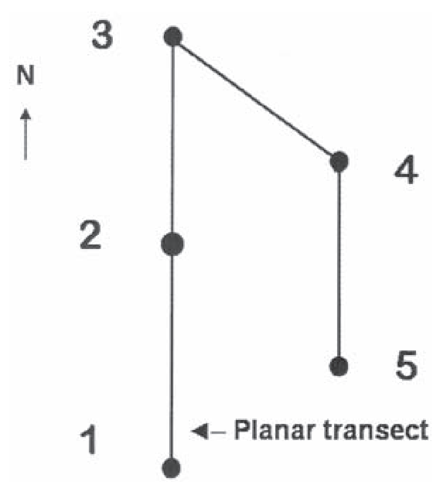


Figure 3—Plot design used at the Savannah River Site showing standard orientation of the 5 subplots and the 4 planar transects.

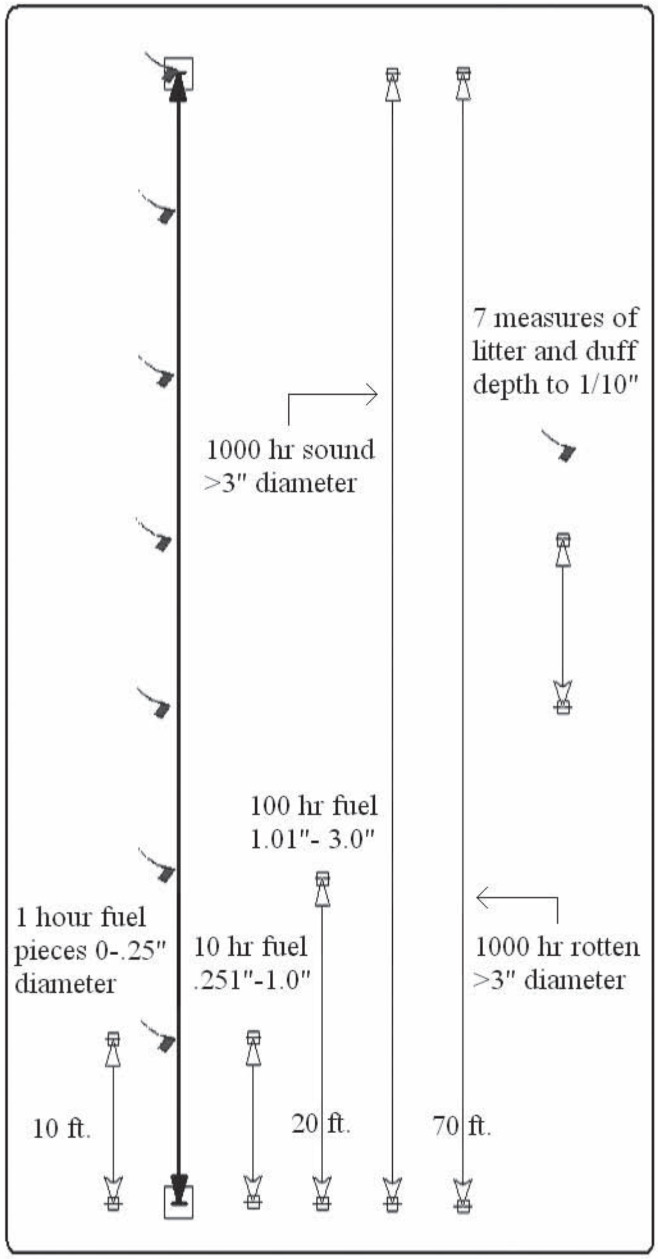


Figure 4—Design of the Brown's planar transect for measuring coarse woody debris and litter and duff depths.

rotten. Seven measurements of litter and duff depth to the nearest 1/10th inch were taken at ten-foot intervals along each of the 70-foot transect lines. An inventory of 622 plots (from the 719 possible) was started in March 1999 and completed in January 2002.

Bulk Density Study

Because of deficiencies in south-wide data on litter-duff bulk densities, which are the fuels most often consumed in prescribed fires, a study was undertaken to develop new bulk density relationships. There have been several studies in the past to collect bulk density values for forested areas of the south. However, these studies were very limited in scope (Scholl and Waldrop 1999) or were completed at locations other than at the Savannah River Site (Ottmar and Vihnanek 2000; Ottmar and others 2003; McNab and others 1978). The primary objective for the study was to determine bulk density conversion factors to convert litter and duff depth values in inches to forest floor fuel values in tons per acre. This was done for combinations of four common forest types (loblolly/slash pine, longleaf pine, pine and hardwood mix, upland hardwood), 3 age classes (5-20, 20-40, 40+ years old) and 3 categories of burning history (0-3, 3-10, 10+ years since last burn).

Bulk density sampling points were randomly selected from the 622 inventory plots of the 1999-2002 inventory period. Random points were selected from groups of plots based on the aforementioned stand type, stand age, and rough age. Within each sample site, subplot 1 was designated as the plot center. The lower left bulk density sample square point was established 33 feet from the plot center at each of the four cardinal directions (figure 5). A 12-inch beveled steel square was positioned on top of the forest floor. Twelve markers (6 inch gutter nails) were then placed in a grid pattern evenly within the square (figure 5). The nails were tapped downwards until the top of the

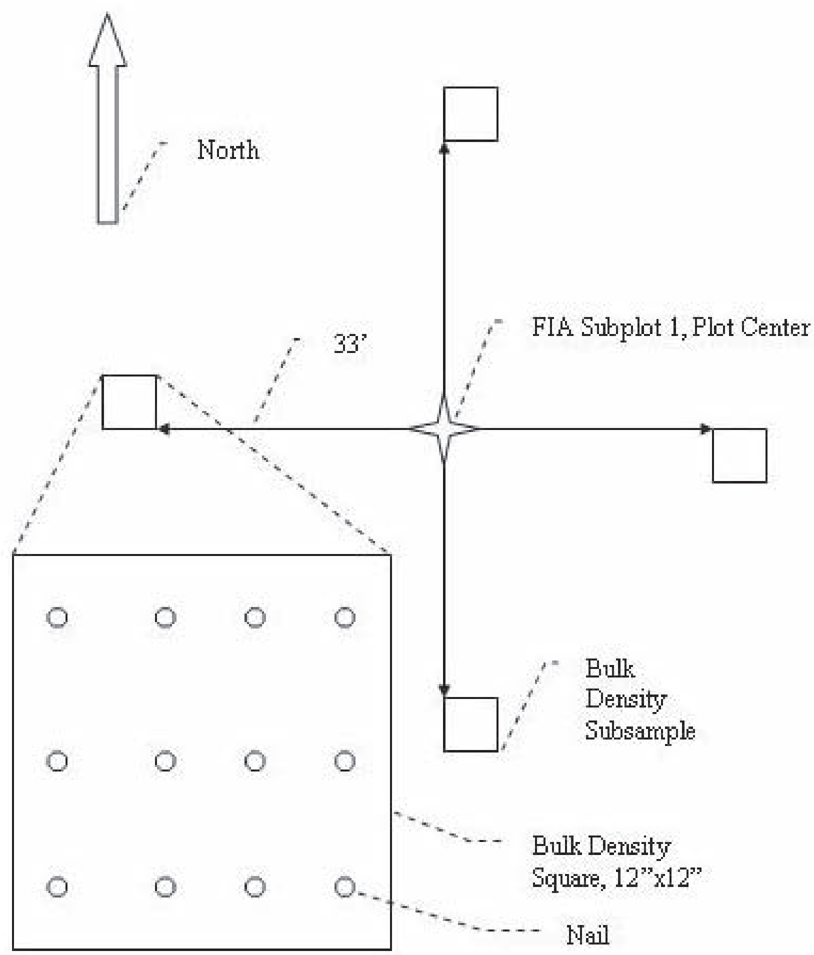


Figure 5—Sample plot layout for the Savannah River bulk density project.

nail was flush with the top of the litter layer. Litter was then carefully removed from the square and placed within a labeled bag. The distance between the top of each marker and the top of the duff layer was measured and recorded. The average of these twelve depth measurements represents the litter depth for the sample. After measurements were recorded, the markers (nails) were again tapped down so that the tops were all flush with the top of the duff layer. The duff layer was then carefully removed, placed in a labeled bag, and the distance between the top of the marker and the substrate was measured, the average of these twelve measurements represents the duff depth for the sample. All litter and duff samples were taken to the lab and oven dried for 48 hours. Litter samples were dried at 70 degrees Celsius and duff samples at 100 degrees Celsius. For further details and results see Maier and others (2004) and Parresol (2005).

Fuels Computation

Computation of biomass for each fuel component was done in a different fashion. For ladder fuels (i.e., non-merchantable arborescents of *Pinus*, *Juniperous*, *Taxodium* < 5" dbh and hardwoods < 6" dbh) biomass equations were utilized (Brown and others 1997). The coarse woody debris subcomponents were converted to biomass using formulas from Brown (1974). These formulas to compute tons/ac are:

$$\text{0- to 3-inch material:} \quad = \frac{11.64 \times n \times d^2 \times s \times a \times c}{L}$$

$$\text{3+-inch material} \quad : \quad = \frac{11.64 \times \Sigma d^2 \times s \times a \times c}{L}$$

where *n* is number of particles counted in each size class along a line transect, *d* is average particle diameter for the 0- to 3-inch size classes and *d* is measured diameter for pieces 3"+, *s* is wood specific gravity, *a* is the nonhorizontal angle correction factor (the correction factor adjusts weight estimates for the fact that all particles do not lie horizontally as assumed in the planar intersect theory), *c* is the slope correction factor for converting weight/ac on a slope basis to a horizontal basis, and *L* is the transect length in ft. The percent slope was measured at each inventory plot and the slope correction factor was calculated as $c = \sqrt{1 + (\text{percent slope}/100)^2}$. The following values for average d^2, *s*, *a*, and *L* were used:

Size class	d^2	s	a	L
0 – 0.25"	0.0151	0.7	1.13	40
0.25" - 1"	0.289	0.7	1.13	40
1" - 3"	2.76	0.58	1	80
3"+ sound	—	0.58	1	280
3"+ rotten	—	0.3	1	280

For the litter and duff calculations subplots were averaged for a combined average litter-duff depth for each inventory plot. Bulk density conversion factors determined from the bulk density study were applied to the averaged depth value for each plot to compute litter-duff tons/ac. See Parresol (2004) for a detailed description of the fuel loading computations.

Broad Species Groups

The SRS contains 25 naturally occurring mixtures of species or stand types (see Hansen and others 1992). For analysis purposes we grouped the 25 stand types into seven broad species composition groupings defined on the basis of the forest types as given in table 1. For each of the 622 inventory plots, a forest type was assigned based on each individual plot species make-up, by applying the following Forest Service definitions:

1) to be assigned to one of the three yellow pine forest types, 70% or more of the total basal area of the stand must be in yellow pine, and then it is assigned to a particular yellow pine species based on the species (loblolly, longleaf, or slash pine) with the largest basal area component,
2) to be assigned to the pine-hardwood type the plot must have ≥50% and <70% of the total basal area in yellow pines species,
3) to be assigned to the hardwood-pine type the plot must have >30% and <50% of the total basal area in yellow pines species, and
4) to be assigned to the hardwood type, < 30% of the total stand basal area must be in yellow pine species.
5) to be assigned to the cypress/tupelo type, ≥50% of the total stand basal area must be in baldcypress (*Taxodium distichum*)and/or tupelo (*Nyssa* sp.).

The inventory plots were grouped into the broad categories previously identified in table 1 based on their observed species make up derived from applying the above definitions. Examples of forest types are shown in figure 6. This resulted in the distribution of inventory plots into the forest type groups as given in table 1. The cypress/tupelo stands are set-aside areas and are not considered further.

Analysis

For analysis purposes we combined litter and duff, and added all components for total fuel. For each broad species group we ran a factorial analysis of variance (ANOVA) on 5 factors, site index class (SIC) where site index (SI) is stand height in ft at 50 years, basal area class (BAC) where basal area (BA) is measured in ft^2/ac, age class (AC) where age is years, number of burns class (NBC) where number of burns (NB) is a count of prescribed burns in a stand,

Table 1—The forest stands on the Savannah River Site categorized into seven broad species composition groups linked with the relevant Forest Service forest types.

Group	Group Name	Forest Types Included	# Stands	Acres	Percent	# Plots
1	Loblolly pine	25, 31, 32	1897	62,602	34.32	277
2	Longleaf pine	21, 26, 34	1151	43,294	23.73	129
3	Slash pine	22	618	17,716	9.71	58
4	Pine-Hardwood mix	12, 13, 14, 35	272	5,340	2.93	23
5	Hardwood-Pine mix	44, 46, 47, 48, 49	214	5,355	2.94	27
6	Hardwoods	51, 52, 53, 54, 56, 57, 58, 61, 62, 63, 64, 68, 72, 82, 98	1739	41,436	22.71	103
7	Cypress/Tupelo	67	118	6,677	3.66	5
			6,009	182,420	100.00	622

a

b

Figure 6—Examples of forest types occuring on the Savannah River Site: a) longleaf pine plantation, b) natural stand of mixed hardwoods.

and number of years since last burn class (YSBC) where years since last burn (YSB) is time in years or fraction thereof from the most recent prescribed burn. The definition of SIC is: if SI < 70 ft then SIC=1, if 70 < SI ≤ 80 then SIC=2, if SI > 80 then SIC=3. The definition of BAC is: if plot BA ≤ 82.5 ft^2/ac then BAC=1, if 82.5 < BA ≤ 111.5 then BAC=2, if plot BA > 111.5 then BAC=3. The definition of age class (AC) is: if age ≤ 4 then AC='A, if 5 ≤ age ≤ 17 then AC='B', if 18 ≤ age ≤ 35 then AC='C', if age ≥ 36 then AC='D'. Number of burns class is 0, 1, 2, 3+. Years since last burn class is defined as: if YSB ≤ 3 then YSBC=1, if 4 ≤ YSB ≤ 9 then YSBC=2, if YSB ≥ 10 then YSBC=3. We also examined the impact of the 5 analysis variables through running a series of stepwise linear least squares regressions by broad species group. To examine trends in more detail, that is, to investigate the role of stand dynamics and effect of prescribed burning, we present a series of regression response surfaces using longleaf pine to illustrate.

Results

Bulk Density Study

Bulk density conversion factors are given in table 2. Average litter bulk densities ranged from 1.5 tons/ac/in for mixed pine and hardwood stands between 5-20 years old without fire for over 10 years to 2.4 tons/ac/in for loblolly and slash pine sites between 5 and 20 years in age and more than 3 years since fire. Average duff bulk densities ranged from 2.6 tons/ac/in on mixed upland hardwood stands between 5 and 20 years in age with greater than 10 years since fire to 9.0 tons/ac/in for loblolly and slash pine greater than 40 years in age and 3 to 10 years since fire.

Fuel Loading

Fuel loading weight in tons across the entire SRS are given in table 3 by broad forest type. Fuel weights are displayed by the fuel categories conifer fuel trees, hardwood fuel trees, CWD, and litter-duff. Table 4 has the same structure as table 3 except average fuel weight in tons per acre is given in

Table 2—Litter and duff bulk densities (tons/acre/inch) for forest types by age class (years) and rough age (years).

		Forest Type							
Age	Rough	Lob/Slash		LL		PH Mix		UH Mix	
Class	Age	Litter	Duff	Litter	Duff	Litter	Duff	Litter	Duff
	0-3	—	—	1.8	3.8	—	—	—	—
5-20	3-10	2.0	4.4	1.6	4.5	—	—	—	—
	10+	1.9	4.8	1.8	4.1	1.5	3.9	1.8	2.6
	0-3	2.4	6.0	2.6	8.2	2.8	6.7	—	—
21-40	3-10	2.4	6.4	2.9	6.3	1.6	5.3	1.9	5.1
	10+	1.9	5.9	2.7	8.6	1.7	4.0	2.1	5.7
	0-3	1.9	6.4	2.2	8.2	2.1	8.8	2.2	6.6
40+	3-10	2.3	9.0	2.1	7.0	2.2	7.0	1.9	6.2
	10+	2.3	7.2	2.5	8.2	2.0	5.3	2.0	7.1

Note: Lob is loblolly pine, LL is longleaf pine, PH Mix is mixed species pine-hardwood stand, UH Mix is mixed species upland hardwood stand, and rough age is number of years since last burn.

Table 3—Fuel loadings in tons from the 1999-2002 Savannah River Site inventory of 622 plots.

	Forest Type						
Fuel Type	Loblolly	Longleaf	Slash	Pine-Hdwd	Hdwd-Pine	Hdwd	All Types
	Tons						
Conifer trees	160,949.2	86,854.5	36,242.4	1,821.3	15.5	4,120.8	290,003.7
Hdwd trees	232,256.3	80,439.4	50,093.5	34,619.4	40,828.3	314,243.7	752,480.6
CWD	233,994.5	150,301.2	79,926.2	28,655.6	22,147.1	149,620.5	664,645.1
Litter-duff	93,503.5	58,705.5	31,645.3	6,476.7	5,402.6	36,668.3	232,401.9
						Overall Total:	1,939,531.3

Note: Hdwd is hardwood, CWD is coarse woody debris.

Table 4—Average fuel loadings in tons/ac from the 1999-2002 Savannah River Site inventory of 622 plots.

	Forest Type						
Fuel Type	Loblolly	Longleaf	Slash	Pine-Hdwd	Hdwd-Pine	Hdwd	All Types
	Tons						
Conifer trees	2.571	2.006	2.046	0.357	0.003	0.107	1.684
Hdwd trees	3.710	1.858	2.828	6.784	8.109	8.167	4.369
CWD	3.738	3.472	4.512	5.615	4.399	3.888	3.859
Litter-duff	1.494	1.356	1.786	1.269	1.073	0.953	1.349
						Average:	11.261

Note: Hdwd is hardwood, CWD is coarse woody debris.

the table cells. The overall fuel tonnage for the 172,228 acres covered in the fuels inventory is 1,939,531 tons giving an average per acre value of 11.3 tons. This average breaks down as follows: 1.7 tons/ac in conifer fuel trees, 4.4 tons/ac in hardwood fuel trees, 3.9 tons/ac in CWD, and 1.3 tons/ac in litter/duff.

Analysis of Variance

The results of the ANOVAs are outlined in table 5. All factors shown in table 5 were significant at the $\alpha = 0.05$ level. As can be seen in this table, loblolly and longleaf pine had a number of significant factors. Our explanation for the nonsignificance with slash involves land-use history. Slash is an off-site species, planted primarily in old-fields with a small range in age, BA and SI, so there is very little variability among the stands. However, using stand variables as a continuum in the linear regressions shows significant effects despite the small range in values, as seen in the next section. The ANOVAs indicate the complex interplay of factors involved in trying to understand fuel loadings.

Table 5—Significant (P<0.05) class variables and interactions by forest type.

Forest Type	Ladder Fuel	CWD	Litter-Duff	Total Fuel
Loblolly	BAC, AC, SIC×YSBC, NBC×YSBC	AC	BAC, AC, SIC×BAC	None
Longleaf	SIC, BAC, AC BAC×AC SIC×YSBC	BAC, SIC×AC, SIC×NBC	None BAC×AC	SIC, BAC, AC
Slash	None	None	None	None
Pine-Hdwd	BAC, NBC	None	None	None

Note: Hdwd is hardwood, CWD is coarse woody debris, BAC is basal area class, AC is age class, SIC is site index class, YSBC is years since last prescribed burn class, and NBC is number of prescribed burns class. Please see text for definitions of classes.

Stepwise Linear Least Squares Regressions

More informative than the ANOVAs are the inferences from the linear regressions. The significant variables from the linear regressions are given in the table 6. Basal area and age are important explanatory variables for estimating fuel loading in loblolly pine stands. In terms of prescribed burning, loblolly ladder fuel and CWD were affected by years since last burn, while the litter-duff layers were affected by number of burns. Site index, basal area and stand age were all critical in determining longleaf pine stand fuel loadings. For longleaf, ladder fuel was affected by years since last burn, but burning in this linear context did not seem to affect the CWD or litter-duff layers. Because of the importance of longleaf pine management at the SRS, response was examined more closely using nonlinear models and log-transformed models. Those results are given in the next section. For slash pine, years since the last burn was correlated with CWD and number of burns affected the litter-duff layers. Finally for the pine-hardwood mix, the CWD was correlated with years since last burn. While stand characteristics play a major role in overall fuel loads, the prescribed burning program is having significant impacts on reducing fuel components.

Response Surfaces

To more fully understand the effects of stand variables and the impact of the prescribed burning program, a series of best-fit empirical regression relationships for longleaf pine were developed to generate response surfaces. Equations for ladder fuel (equation 1), litter-duff (equation 2), 1 hour fuel

Table 6—Signicant variables (P<0.05) from the stepwise linear least squares regressions.

Forest Type	Ladder Fuel	CWD	Litter-Duff	Total Fuel
Loblolly	BA, A, YSB	A, YSB	BA, A, NB	BA
Longleaf	SI, BA, A, YSB	SI, BA, A	BA	SI, BA, A, YSB
Slash	SI, BA	YSB	BA, NB	BA
Pine-Hdwd	SI, BA	SI,YSB	None	BA

Note: Hdwd is hardwood, BA is basal area in ft^2/ac, A is age in yeasrs, SI is site index in ft base age 50, YSB is years since last prescribed burn, and NB is number of prescribed burns.

(equation 3), 10 hour fuel (equation 4), and the 100+ hour fuel (equation 5) are given below.

$$\widehat{ladder\ fuel} = 50.217\,exp\left(-0.036SI + 0.014BA - 0.033Age + 0.00102YSB^2\right) \qquad (1)$$
$$R^2 = 0.51, RMSE = 3.50$$

$$\widehat{litter\text{-}duff} = 0.598 + 0.0127BA - 0.374 / YSB \qquad (2)$$
$$R^2 = 0.45, RMSE = 0.57$$

$$\widehat{\ln 1 hour\ \ fuel} = 4.082 - 0.206 \ln Age - 1.659 \ln SI - 0.257 \ln NB \qquad (3)$$
$$R^2 = 0.084, RMSE = 0.966$$

$$\widehat{\ln 10 hour\ \ fuel} = -1.429 + 0.272 \ln Age + 0.075 \ln YSB \qquad (4)$$
$$R^2 = 0.11, RMSE = 0.836$$

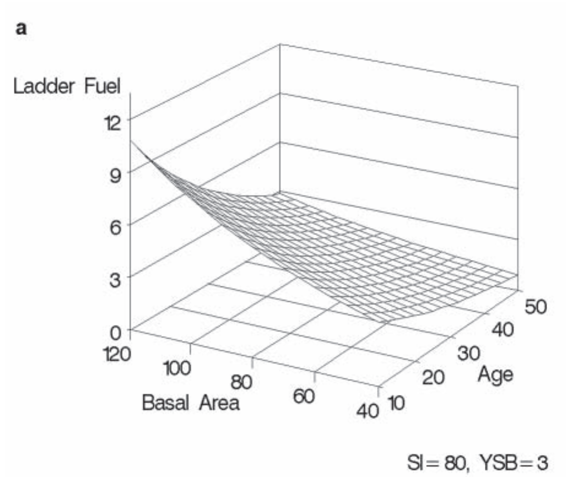
$$\widehat{\ln 100 + hour\ \ fuel} = -6.071 - 0.939 \ln BA + 0.803 \ln Age + 1.710 \ln SI \qquad (5)$$
$$R^2 = 0.15, RMSE = 1.373$$

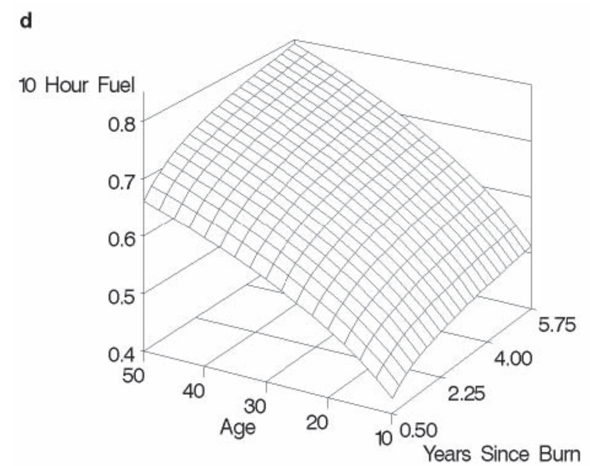
Figure 7 shows the response surfaces generated from these equations. Figure 7a shows that ladder fuels are generally determined by BA and age, decreasing as BA decreases and age increases. Equation 1 shows that YSB has a small but statistically significant effect in reducing ladder fuels. Figure 7b shows the dramatic effect both YSB and BA has on determining litter and duff fuel loading. It is clear that litter-duff loadings recover quickly, in as little as two to three years after a burn. Figure 7c shows that the 1 hour fuel is reduced through repeated burning and that SI also plays a role. Figure 7d indicates that recency of burn has some impact on the 10 hour fuel but that age is the main factor determining fuel load. Finally, equation 5 and figure 7e reveal that burning has no detectable effect on the 100+ hour fuel, but rather the interplay of age, BA and SI.

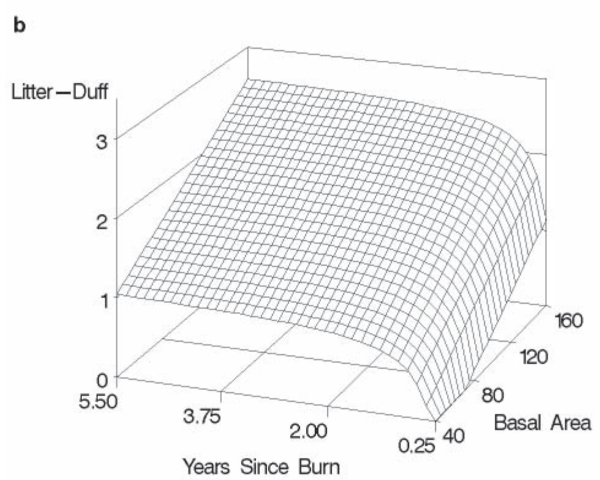
Discussion

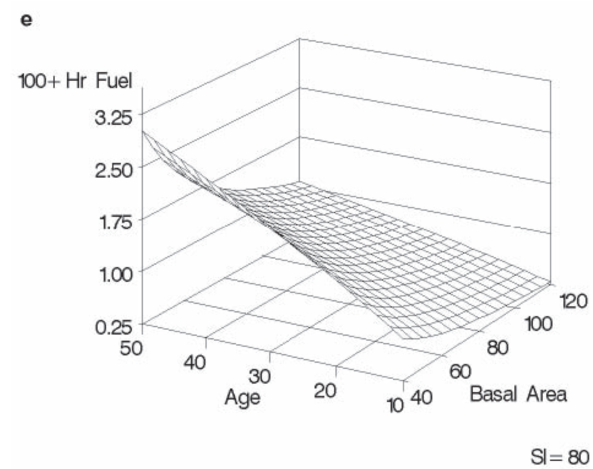
Field fuel inventories are generally not available at local, regional or national scales. At the SRS managers identified the need for such information to help guide decision making concerning fuels management. We easily modified standard forest inventory methods to incorporate a complete assessment of fuel components on the SRS. The FIA program of the USDA Forest Service inventories the entire U.S. forest resources periodically and is moving towards an annual multi-resource inventory system. A suite of habitat and environmental variables are collected along with the more traditional tree measurements. From our experience with this project, we were able to easily incorporate fuel variables into our inventory design and we strongly believe and recommend that the FIA program nationally can achieve the same objective. The average number of man days per plot was equal to the expected productivity without the fuel loading modification.

Due to the paucity of forest floor bulk density information for southeastern forests, new bulk density conversion factors for the dominant forest types on the SRS were developed to compute litter and duff fuel loading in tons/ac/in.









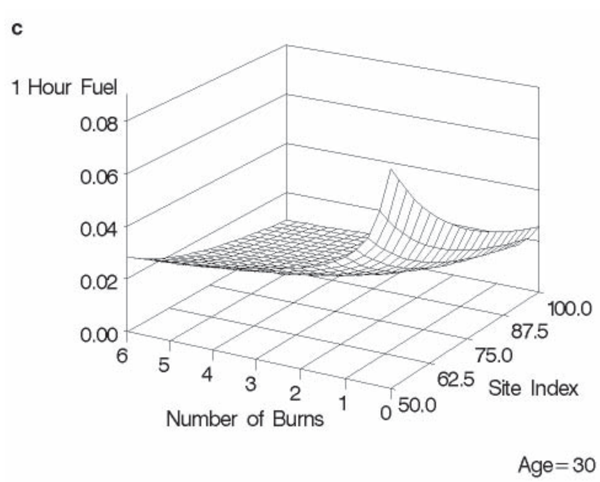


Figure 7—Response surfaces illustrating trends in fuel levels as a function of stand variables and burning history: a) ladder fuel based on equation 1, b) litter-duff fuel based on equation 2, c) 1 hour fuel based on equation 3, d) 10 hour fuel based on equation 4, and e) 100+ hour fuel based on equation 5.

These conversion factors should prove useful for similar forest types of the upper coastal plain and piedmont forests of the Southeastern U.S.

The pattern of fuel loading across the forest types, age, stocking and fire frequency reflects land use history, stand dynamics, stand management and fire management. For the major forest types (loblolly, longleaf, slash, pine-hardwood, hardwood-pine, and hardwood) stand variables generally explained the larger fraction of the variability in the fuel components. Age, BA, and SI explained a large proportion of the variability in individual components, but particularly ladder fuels and 100 hour+ fuels. Natural stand dynamics even in these highly disturbed systems dominated the observed relationships. Ladder fuels decreased with age probably as a result of two factors. Small trees and shrubs are predominant in young stands simply as a result of early succession. As the stands age, the mid-story shrub component is suppressed by the overstory. In addition, land use history also plays a role on these sites. The older pine types were generally planted on old-fields established during the 1950's. These stands had most of the hardwood shrub component eliminated through farming. Later plantations were established in cut-over lands with little effected control of the competition. More recent stands were established on an array of sites with a wide range in ladder fuel species development.

In contrast, stand management probably has a major influence on the relationship between BA and ladder fuels for the managed pine types. The lower BA stands have reduced ladder fuels and mid-story components as a result of disturbance from mechanical harvesting through repeated thinning operations, coupled with prescribed fire. The only fire variable affecting ladder fuels was YSB, but the impact was relatively small. Restriction on environmental conductions during prescribed burning, particularly wind, humidity, and fuel stick moisture, probably limits the fire intensity such that only smaller diameter woody trees and shrubs are killed or controlled. Most prescribed fire activities have also historically been applied during the dormant season, in contrast to the growing season. The latter period is recommended for burning when the objective is to control mid-story shrubs and ladder fuels.

The major fuel type controlling surface fire rate of spread in these stands is the litter and duff and the 1 hour fuel components. Numerous studies of prescribed burning fuel consumption at the SRS demonstrated that these components are the largest fraction contributing to fuel consumption following burning (Kilgo and Blake 2005). Using longleaf pine as an example, it is clear that the previous dominant management paradigm that stands should be burned every five to seven years may not be an effective frequency to reduce hazard fuels within stands. Not withstanding the influence of the spatial distribution of fuel treatments on the rate of spread of catastrophic large wildfire, it appears that a two-to three year burning cycle is critical to effectively reduce these fuels (Outcalt and Wade 2004). This study has established a baseline for future fuels management and policies and provides insight into factors contributing to fuel dynamics for upper coastal plain forests.

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Variation in Surface and Crown Fire Hazard With Stand Age in Managed Coastal Western Hemlock Zone Forests in Southwestern British Columbia

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***Abstract**—Surface and crown fuels were measured in 186 stands ranging in age from 0 years after clearcutting to old-growth forests > 300 years old in Douglas-fir (*Pseudotsuga menziesii*) – western hemlock (*Tsuga heterophylla*) – western redcedar (*Thuja plicata*) – dominated forests in southwestern British Columbia. Indexes of surface fire hazard based on woody debris loads, and of crown fire hazard based on 5 factors (canopy foliar bulk density, height to live crown, woody debris loads, ladder fuels, and snag quantities), were developed. Using the indexes developed, surface fire hazard followed a U-shaped trend with stand age, being highest for the first few years after clearcutting, declining to a minimum 20 to 40 years after harvesting before increasing. Crown fire hazard was lowest for the first few years after clearcutting, rose to a maximum 20 to 90 years after harvesting and then declined to low values in 100 to 150 year old forest, before rising to higher values in old-growth. In the absence of fuel reduction treatments, some post-harvesting age classes of forests will have higher surface or crown fire hazards than old-growth forests.*

Introduction

Fuel management in forests of southern coastal British Columbia, dominated by Douglas-fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*), and western redcedar (*Thuja plicata*), in the recent past has been characterized by a dichotomy. On the one hand, in active forest harvesting areas, strips of old-growth forest were left between clearcut blocks partly because it was believed that the old-growth strips could serve as fuel breaks as they presented a lower fire hazard than the clearcuts (Grant 1984). On the other hand, in the water supply watersheds for the city of Vancouver, management involved clearcutting old-growth forests to produce younger plantations with a perceived lower fire hazard state (Economic and Engineering Services 1991). This raised the question of how fire hazard varied with forest age.

Forest fire hazard (a fuel complex defined by volume, type, condition, arrangement, and location, that determines the degree both of ease of ignition and of fire suppression difficulty (Forest Resources Development Branch 1986)) can be broken into two components – surface fire hazard and crown fire hazard – which are not necessarily correlated. Assuming surface fire hazard is directly related to surface fuel quantity, different trends with stand age in surface fire hazard have been reported. Brown and See (1981) described three different trends for lodgepole pine (*Pinus contorta*) as well as for subalpine fir (*Abies lasiocarpa*) forests in the U.S. Rocky Mountains – i) a general increase with age, peaking in old-growth, ii) an inverse U-shaped curve with a peak occurring in mature (110 – 160-year old) forests, and iii) a U-shaped curve

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with maximum values occurring in the youngest as well as the oldest forests. Most studies have found U-shaped curves (Feller 2003), particularly in B.C. and the adjacent U.S. Pacific Northwest (Agee and Huff 1987; Fahnestock 1976; Spies and others 1988; Wells and Trofymow 1997).

In areas subjected to forest harvesting, surface fire hazard for the first few years after harvesting can be greater than at any other time in the life of a forest due to inputs of logging slash (Feller 2003; Wells and Trofymow 1997). Feller (2003) considered that a U-shaped curve could be the normal trend in surface fire hazard with forest age after harvesting, with deviations from this occurring for different reasons. For example, initial hazard may not be particularly high if initial post-disturbance inputs are low as a result of a severe fire, slow collapse of snags, or low pre-disturbance vegetation or surface fuel biomass. An inverse U-shaped curve may occur if thinning occurs or if tree mortality is particularly high during the mid-life period of a forest as a result of high tree densities, insects, disease or blowdown.

Surface fire hazard is likely to depend not only on the total surface fuel load, but also on the distribution of size classes and decay states of surface fuels (Baker 2003; Van Wagner 1983). Baker (2003) considered that large sound fuels are relatively unimportant to fire behaviour since they are usually not consumed, while large well-decayed fuels and fine fuels were considered important. Fine fuels may increase slowly after a fire for 150-200 years, and then decline, while large sound fuels, legacies of the pre-disturbance forest, generally decrease with time for long periods until they are replenished again (Baker 2003; Harmon and others 1986; Romme 1982). Van Wagner (1983) proposed that surface fire hazard in northern coniferous forests peaked before canopy closure and again in old-growth forests, primarily due to fluctuations in the quantity of fine fuels present.

Crown fire hazard depends on the ease of initiation and of propagation of crown fires. Van Wagner (1977) developed conceptual models of both initiation and propagation, and most subsequent work on crown fire hazard has used these models (for example, Cruz and others 2003; Scott and Reinhardt 2001). According to Van Wagner (1977), ease of initiation depends on the intensity of the surface fire, the height above the ground of the base of the live canopy, and foliar moisture content. Ladder fuels can be considered to either increase the surface fire intensity or increase flame length (Alexander 1988), or decrease canopy height (Van Wagner 1993), facilitating crown fire initiation. Once in the crowns, ease of propagation depends on the bulk density of available fuel in the canopy as well as rate of spread of the fire which in turn, depends on wind speed. Scott and Reinhardt (2001), using Van Wagner's (1977) conceptual models, developed a quantitative Torching Index and Crowning Index, but did not sample surface and crown fuels across all forest ages. The Canadian Fire Behavior Prediction System indicates that crown fire intensity and spread rate are greater in immature than in mature lodgepole pine forests for a given set of fuel moisture conditions (Forestry Canada Fire Danger Group 1992). No study, however, appears to have determined an index of crown fire hazard for an entire range of age classes of a forest, although Van Wagner (1983) has proposed that crown fire hazard was greatest in young stands with closed canopies, then decreased before increasing again in old-growth stands. Fahnestock (1976), using fire hazard keys, reported a similar trend in subalpine fir – false box (*Pachistima myrsinities*) forests in north central Washington, but Hawkes (1979), using Fahnestock's keys, found little difference in crowning potential between young and old-growth stands in Canada's southern Rocky Mountains in Alberta.

Due to the contrasting beliefs about the fire hazard in old-growth versus managed forests and the lack of quantitative data on successional changes in forest fire hazard in southwestern British Columbia, this study was begun in 1994 with the objective of determining the relative surface and crown fire hazards of old-growth forests, and those arising from a forest harvesting regime.

Study Area

The study occurred in the Coastal Western Hemlock biogeoclimatic zone of southwestern British Columbia, within 50 km from the city of Vancouver, specifically in the dry maritime (CWHdm) and very wet maritime (CWHvm) biogeoclimatic subzones (Meidinger and Pojar 1991).

A total of 186 study plots, each approximately 0.5 to 1 ha in size, were located in old-growth forests and adjacent areas that had been clearcut up to 80 years previously, or burned from 80 to 150 years previously. No stands aged 151 to 250 years old were sampled due to their unavailability. All stands older than 250 years, regardless of their actual age, were classed as old-growth. Clearcuts up to 60 years old had not been subjected to any slash disposal treatment and had mostly been planted with Douglas-fir. All forests were dominated by western hemlock, western redcedar, and Douglas-fir and, at higher elevations, Pacific silver fir (*Abies amabilis*) as well. All study plots were located on sites intermediate in moisture and nutrient status to avoid the confounding factor of site variability.

The CWHdm and CWHvm subzones have wet mild climates, with mean annual precipitation of 1800 to 2800 mm, most of which is rain, and mean annual temperatures of 8 to 10° C. All months have mean temperatures > 0° C. Due to the high forest productivity resulting from this climate, relatively long intervals between fires, and the presence of slowly decaying western redcedar, old-growth CWH forests generally contain the greatest surface fuel loads of all B.C. old-growth forests (Feller 2003).

Methods

Field Measurements

Within each study plot, 3 surface fuel plots and 3 crown fuel plots were randomly located. Each surface fuel plot consisted of an equilateral triangle with 20 m or 30 m sides, depending on fuel load and spatial orientation of the study plot. The mass of all surface woody fuels > 1 cm diameter was determined using the line intersect technique (Van Wagner 1968) measuring along the sides of the triangles. Each piece measured had its species or decay state recorded. Volumes calculated from the line intersects were converted to masses using relative densities determined for each size class (1.l-3.0, 3.1-5.0, 5.1-7.0, 7.1-12.0, and > 12 cm) for each species and decay class present. Nine to 32 samples per size class for each species or decay class were cut from randomly chosen woody materials and taken to the laboratory for density analysis. Fine fuels (≤ 1 cm diameter) were collected from nine 1 m^2 plots, each located 2 m away from each triangle apex along a line projected outwards from the centre of the triangle.

Each crown fuel plot consisted of a 20 x 20 m or 20 x 10 m plot, depending on spatial orientation of the study plot. Within each crown fuel plot, the species and d.b.h. of every tree present was measured. The dominance class and state of decay of each snag present were also recorded. Canopy volume was estimated by multiplying surface area by crown length, which was measured as the difference between the height to the base of the live crown and the height to the top of the tree canopy, with 1 to 3 measurements per crown fuel plot. Relative ladder fuel amount was estimated visually using a 6 category system. Ladder fuel was considered to be any dead woody material or small conifers occurring between the surface fuel bed (up to 1.5 m above the ground) and the live canopy.

Stand age was determined from forest cover maps where known, or from counting rings in cores extracted from 2 to 3 of the largest trees in each crown fuel plot.

Laboratory Procedures

Surface fuel materials—Relative densities of all woody materials were measured using a water displacement technique and an average value calculated per size class and species or decay class. Fine fuel samples were dried at 100 °C for 24 to 48 hours, then weighed. An average fine fuel mass was calculated from each of the nine samples collected per study plot.

Crown fuel data—For each study plot, an average canopy foliar bulk density, height to the base of the live crown, and relative ladder fuel quantity were calculated from the 3 crown fuel plot values. Canopy foliar bulk density was calculated by dividing the total foliage mass in a plot by the measured crown volume. Foliage mass was estimated by applying foliar biomass equations to the d.b.h. values of all trees measured in a plot. These equations had either been developed by M. Feller or were obtained from Gholz and others (1979).

Development of a surface fire hazard index (SFHI)—Surface fire hazard was considered to depend on the quantity of surface fuels present, particularly on fine fuels (≤ 1 cm diameter). It was assumed that a surface fire was unlikely to start if no fine fuels were present. The surface fire hazard index (SFHI) chosen was

$$\mathrm{SFHI} = \mathrm{FF}\ (1 + \mathrm{CWD})$$

where FF is the quantity (kg/m^2) of fine fuels present, and CWD is the quantity (kg/m^2) of coarse woody debris (materials > 1 cm diameter). The study plots were placed into different age classes then the average SFHI was calculated for each age class. To test the sensitivity of the changes in SFHI with age to different age class groupings and different relative weighting of FF and CWD, the average SFHI was calculated for combinations of six different age class groupings (table 1) and nine different FF/CWD weightings. Thus, for SFHI = FF [1 + a(CWD)], "a" varied from 10 to 0.01.

Development of a crown fire hazard index (CFHI)—Crown fire hazard indexes which combined both initiation and propagation were developed. It was considered that a crown fire would not occur if it could not be initiated or if it could not propagate. Thus -

Crown Fire Hazard Index (CFHI) = (ease of propagation) x (ease of initiation).

Ease of initiation was considered to depend on surface fire intensity, ladder fuels, and height to the live crown, while ease of propagation was considered

Table 1—Different age class groupings used to calculate the Surface and Crown Fire Hazard Indexes and relative weightings of FF and CWD used to calculate the Surface Fire Hazard Index.

Groupings	A	B	C	D	E	F
Age class (years)	0-3	0-2	0-3	0-3	0-2	0-4
	4-9	3-5	4-10	4-9	3-6	5-10
	10-15	6-10	11-18	10-16	7-12	11-20
	16-29	11-20	19-30	17-25	13-20	21-30
	30-40	21-39	31-45	26-35	21-35	31-50
	41-61	40-60	46-65	36-55	36-50	51-70
	62-81	61-80	66-85	56-75	51-70	71-90
	82-105	81-100	86-105	76-100	71-90	91-110
	106-150	101-150	106-150	101-150	91-150	111-150
	>150*	>150	>150	>150	>150	>150

* All forests > 150-years-old were actually > 250 years old and could be considered old-growth.

to depend on canopy foliar bulk density. It was assumed that foliar moisture content would not vary with stand age and could be ignored. Surface fire intensity would depend on surface fire rate of spread and fuel consumption. It was then assumed that rate of spread would be similar beneath forests of different ages and that fuel consumption would depend on surface fuel load. The presence of tall snags (codominant to dominant in canopy height status) with rough surfaces, implying a high probability of blowing embers, was also considered as a factor which might enhance the likelihood of a crown fire.

Therefore, CFHI α [f(FD)] [f(SFL, LF, HC, SD)]

where FD is the canopy foliar density (kg/m^3), SFL is the surface fuel load (kg/m^2), LF is the relative ladder fuel quantity (dimensionless, with scale = 0-5), HC is the height to the live canopy (m), and SD is the density of tall, rough snags (no. snags/ha).

In its simplest form, this equation is CFHI = (FD) (SFL + LF – HC + SD).

The study plots were placed into different age classes then the average CFHI was calculated for each age class. Due to missing tree data, canopy foliar bulk densities could not be calculated for seven plots, so the analyses were conducted using 179 plots. To test the sensitivity of the changes in CFHI with age to different age class groupings and different relative weighting of SFL, LF, HC and SD, the average CFHI was calculated for combinations of six different age class groupings (the same as those used for SFHI (table 1)) and different SFL, LF, HC and SD relative weightings in the CFHI equation. The weighting given to each of these factors was increased or decreased by up to 6-10 times (table 2).

To determine which weighting factors might be most appropriate to use, the outputs from these equations were correlated with the Crowning Index (CI) of Scott and Reinhardt (2001), calculated for drought summer conditions using their figure D-1 for each of the study plots except those aged 0-3 years (table 2). This left 154 study plots for which the CI was calculated. The CI decreases as the ease of crowning increases, whereas the CFHI of the present study increases as the ease of crowning increases. Consequently, equations which produced CFHIs which were positively or weakly negatively ($r > -0.1$) correlated with CI values, were not considered to be appropriate.

Table 2—Pearson correlation coefficients (r) between the CFHI of the present study and the CI of Scott and Reinhardt (2001) for different weightings of SFL, LF, HC, and SD used in the equation CFHI = FD (SFL + LF – HC + SD).

	r			
Weighting	**SFL**	**LF**	**HC**	**SD**
10.00	--	–0.55	--	–0.18
6.00	–0.41	--	0.57	--
5.00	--	–0.61	--	--
4.00	–0.36	--	0.51	–0.16
3.00	–0.31	--	--	--
2.50	--	–0.36	--	--
2.00	–0.22	--	0.31	–0.13
1.67	--	–0.24	--	--
1.33	--	–0.17	--	--
1.00	–0.06	–0.06	–0.06	–0.06
0.67	--	0.07	--	--
0.50	0.03	0.14	–0.38	--
0.40	--	--	--	–0.06
0.33	0.07	0.22	--	--
0.25	0.08	--	–0.53	--
0.20	--	--	--	–0.05
0.17	0.10	0.30	–0.56	--
0.13	--	--	–0.58	--
0.10	--	--	–0.59	–0.05
0.07	--	0.33	--	–0.04

-- not calculated
The equation in which each of SFL, LF, HC, and SD has an equal weighting (1) is CFHI = FD (SFL + 6LF – HC + SD/20)

SFHIs and CFHIs, determined for the 6 different age class groupings were compared using a Kruskal Wallis test to identify significantly different ($P < 0.05$) values. All statistical analyses were conducted using SYSTAT 11 software (SYSTAT 2004).

Results and Discussion

Surface Fire Hazard

Average fine fuel and coarse fuel loads each varied approximately three fold from 0.1 to 0.3 and from 4.2 to 15.2 kg/m^2, respectively (table 3). The SFHI suggested that the surface fire hazard in old growth forests was less than in recently harvested areas, regardless of the relative weighting given to coarse fuels, which varied over 3 orders of magnitude (figure 1). Since the surface fire hazard in old-growth forests, relative to that in recently harvested areas, varied little with the magnitude of the coefficient “a” in SFHI = FF[(1 + a(CWD)], it was decided to use the simplest form of this equation, with a = 1, to express the relative surface fire hazard. When this equation was applied to different age groupings, the general trend in hazard with age was an initial very high hazard (up to five years post-harvest) which declined to

Table 3—Average values, with standard errors in parentheses, of each of the variables used in the SFHI and CFHI equations for each of the age classes assessed in age class grouping F.

Age class	Number of plots	FF	CWD	SFL	FD	LF	HC	SD
(years)		- - - - - - *(kg/m²)*	- - - - - -		*(kg/m³)*		*m*	*(no./ha)*
0 - 4	16	0.29 (0.03)	13.45 (1.56)	13.74 (1.56)	0.00 (0.00)	3.3 (0.6)	0.0 (0.0)	0 (1)
5 - 10	17	0.10 (0.03)	15.15 (1.73)	15.25 (1.74)	0.03 (0.01)	3.9 (0.4)	0.2 (0.1)	4 (3)
11 - 20	14	0.12 (0.03)	9.51 (1.62)	9.63 (1.64)	0.05 (0.01)	3.3 (0.4)	1.4 (0.7)	0 (0)
21 - 30	24	0.12 (0.01)	4.81 (0.52)	4.93 (0.52)	0.13 (0.02)	3.4 (0.2)	7.4 (0.8)	16 (14)
31 - 50	17	0.24 (0.03)	5.64 (0.60)	5.88 (0.62)	0.10 (0.01)	3.6 (0.3)	10.3 (1.0)	150 (44)
51 - 70	19	0.29 (0.05)	6.54 (0.74)	6.83 (0.77)	0.13 (0.01)	2.5 (0.3)	15.9 (1.1)	54 (22)
71 - 90	15	0.23 (0.03)	7.48 (1.62)	7.71 (1.62)	0.13 (0.01)	1.9 (0.3)	17.7 (1.5)	54 (19)
91 - 110	7	0.26 (0.03)	6.93 (0.60)	7.19 (0.60)	0.09 (0.01)	1.4 (0.2)	14.9 (2.0)	69 (12)
111 - 150	18	0.20 (0.03)	4.19 (0.53)	4.39 (0.53)	0.10 (0.01)	1.6 (0.2)	18.8 (1.1)	23 (8)
> 150	32	0.21 (0.02)	10.00 (0.94)	10.21 (0.94)	0.12 (0.01)	2.4 (0.1)	18.9 (1.0)	23 (4)

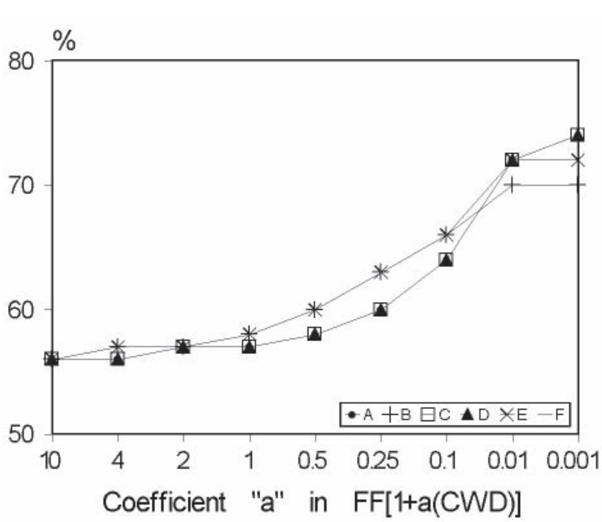

Figure 1—Surface Fire Hazard Index in old-growth forests as a percentage of that in the youngest post-harvesting forests for six different age class groupings (A-F).

a minimum around 20 to 40 years post harvest, followed by an increase to around 50 to 70 years post harvest, a decrease to around 100 to 150 years post harvest, then an increase again in old-growth (figure 2). Old-growth forests, however, generally had a lower surface fire hazard than forests 0 to 5 and 50 to 70 years old (figure 2), although the difference between the old-growth SFHI and the greatest SFHI was statistically significant for age class groupings A, C, D, and F, but not B and E (figure 2). The only age classes which had a statistically significant lower SFHI than that of old-growth were those in the range of 16 to 35 years (figure 2).

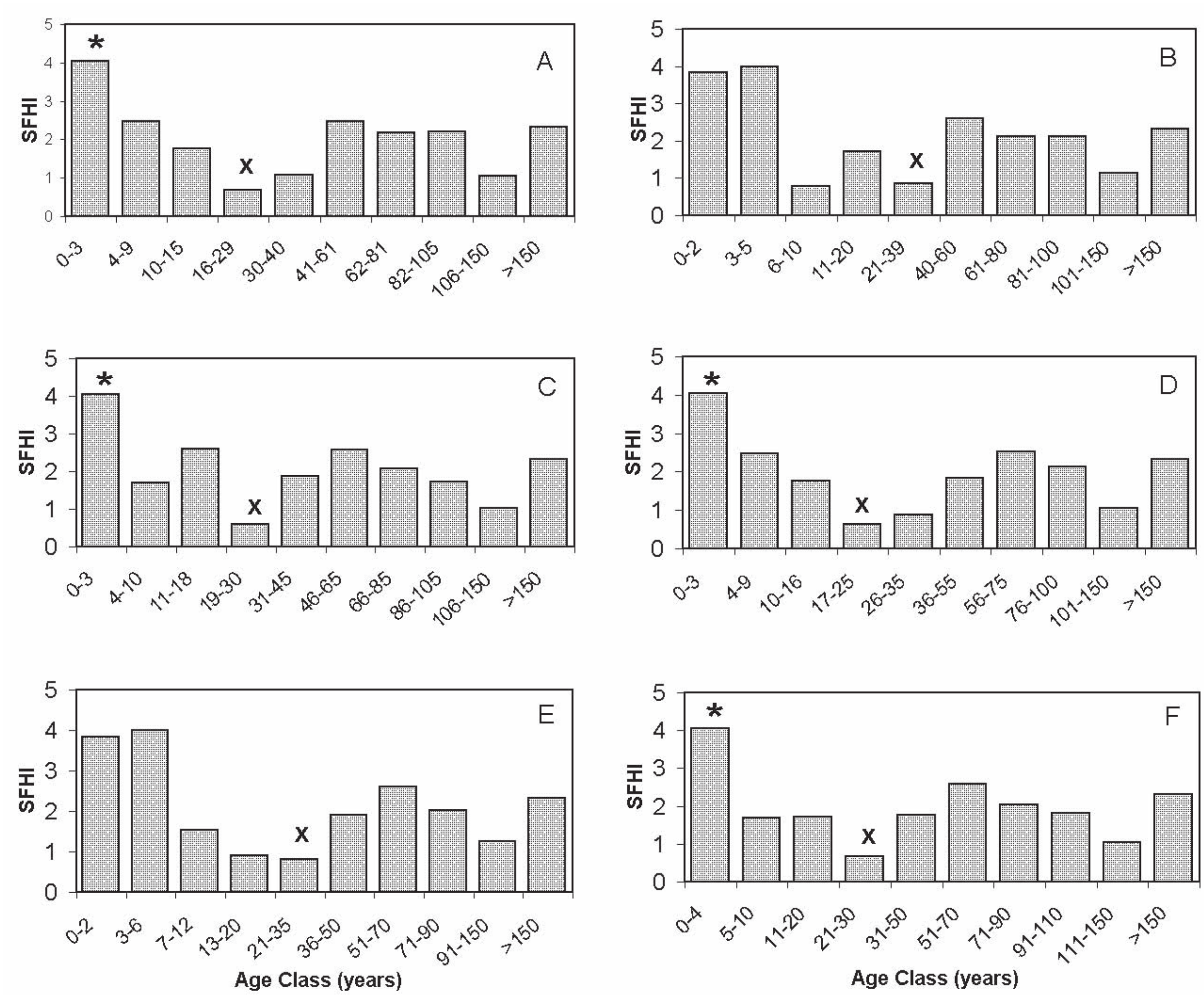

Figure 2—Average Surface Fire Hazard Indexes for different aged forests using six different age class groupings (A-F) and the equation SFHI = FF(1 + CWD).* designates a SFHI which is significantly higher ($P < 0.05$) than that of old-growth. x designates a SFHI which is significantly lower ($P < 0.05$) than that of old-growth.

The SFHI used total CWD and not just well decayed CWD, which has been considered more important in determining surface fire hazard (Baker 2003). Quantitative data to support this do not appear to be available, however. Furthermore, several studies in coastal western hemlock forests have found that well decayed materials constitute a greater proportion of total CWD mass in younger than in old-growth forests (Spies and others 1988; Wells and Trofymow 1997; Feller 2003). Consequently, if the SFHI had given greater weight to well decayed CWD than to less well decayed CWD, the differences in SFHI between old-growth and the youngest forests would likely have been greater. It was also assumed that wind speed was unaffected by forest age. This is unlikely to be correct as wind speed near the ground surface is usually greater in the open than beneath forests (Spittlehouse and others 2004), so fire forward rates of spread, and hence fire hazard would also be greater in the open. Tanskanen and others (2005) have also found that surface fire likelihood in Finnish conifer forests was greatest in recent clearcuts and declined with increasing age up to age 60 years, the oldest forest studied, due to increasing surface fuel moisture content. Consequently, microclimate differences even further emphasize the difference in surface fire hazard between old-growth and the youngest forests. Thus, it can be concluded that the surface fire hazard of the old-growth forests in the study area was less than that of recent clearcuts and was only greater than that of forests around 16 to 35 years old.

Crown Fire Hazard

Average surface fuel loads were greatest in 0 to 10 year old stands and least in 111 to 150 year old stands; average canopy foliar bulk densities increased with age up to 20 years, then remained relatively constant thereafter; ladder fuels were greatest in 0 to 70 year old stands; canopy heights tended to increase with stand age; and the density of dominant rough snags was least in the youngest stands and greatest in stands aged 31 to 110 years (table 3). Canopy foliar bulk densities may be overestimated in some old-growth stands as some of the tallest trees had dead tops and the foliar biomass regression equations used, which had been developed for trees up to 1.6 m d.b.h., were applied to trees up to twice this size.

Although the influence on the CFHI of variations in the weighting given to individual factors was assessed, the influence of variations in the weighting given simultaneously to 2 or more factors was not fully analyzed. Consequently, the appropriate CFHI equations chosen must be considered a first approximation. When the different crown fire initiation variables (whose range in values between individual plots were - SFL = 0.4 to 30.2 kg/m^2, LF = 0 to 5, HC = 0 to 32 m, and SD = 0 to 592 stems/ha) were given equal weight, the CFHI equation became CFHI = FD (SFL + 6LF – HC + SD/20). The weighting given to SFL had a major impact on the relative CFHI of old-growth versus younger forests. As the weighting increased, so did the CFHI of old-growth compared to that of younger forests (figure 3). Correlations between the CFHI and the CI of Scott and Reinhardt (2001) were > -0.1 for weightings of one or less (table 2). Consequently, an appropriate weighting factor would be > 1.

Regardless of the weighting given to LF, HC, or SD, the CFHI always remained lower in old-growth than in younger forests (figure 3). This applied even for weighting factors substantially greater or less than those given in figure 3. Based on correlations between the CI and CFHIs, appropriate weighting factors would be > 1 for LF and SD, and < 1 for HC (table 2).

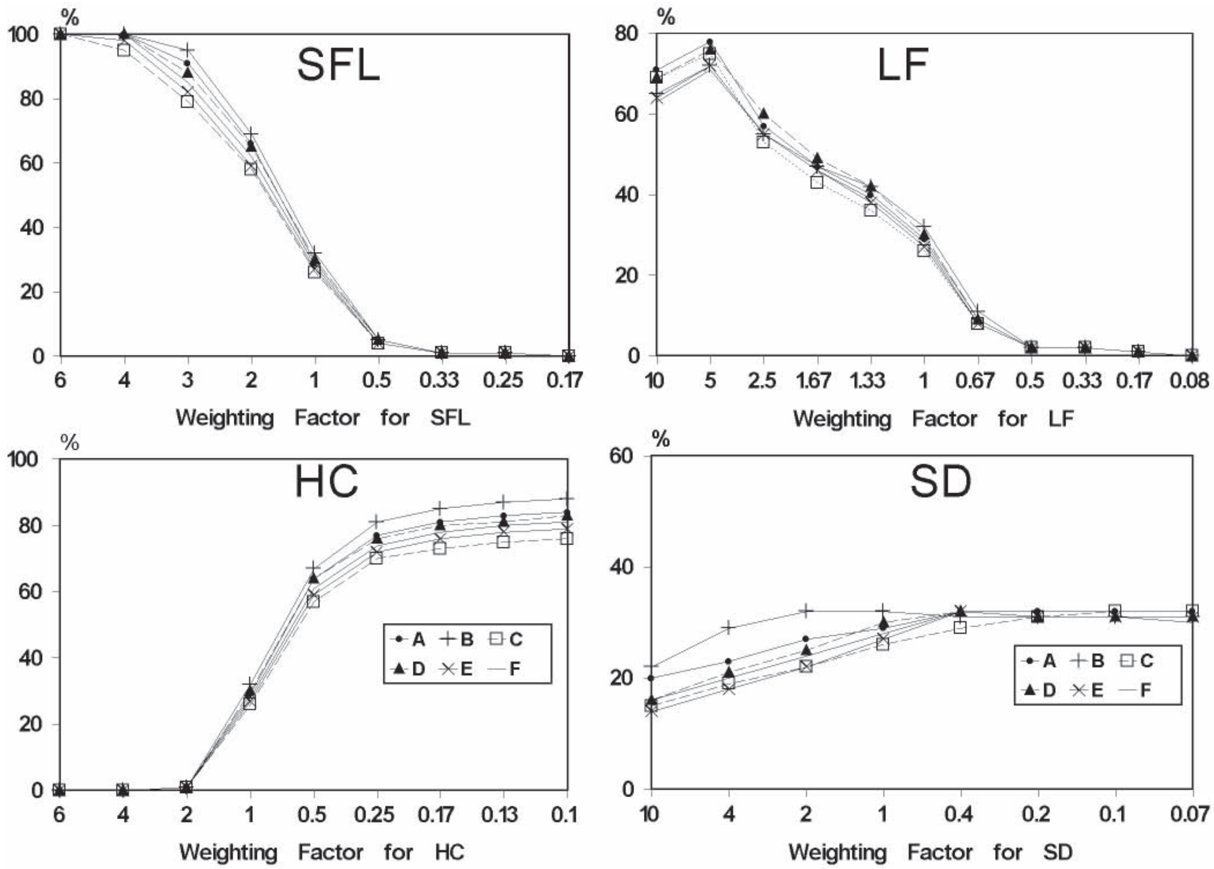

Figure 3—Crown Fire Hazard Index in old-growth forests as a percentage of the highest CFHI in all age classes of forests, using six different age class groupings (A-F) and different weightings for SFL, LF, HC, and SD.

Many possible equations could be chosen using different appropriate weighting factors. All equations with SFL preceded by a coefficient of 4 or less resulted in CFHIs being lower in old-growth than in some younger forests. For simplicity, several equations were chosen for use, using weighting factors that were not too extreme. Due to the lack of data or even theoretical models which link snag abundance to crown fire hazard, the weighting given to snag density was kept relatively low. It is currently unclear which equation best predicts crown fire hazard as none have been tested with real fires. CFHIs calculated from a sequence of equations with increasing weight being given to SFL from equation 1 through equation 4 are given in figure 4. The indexes calculated from the equations CFHI = FD(aSFL + bLF + cHC + dSD), with varying a-d, were multiplied by either 25, 10, or 8 to convert the index to a scale of 1 to 100. The CFHIs calculated from all 4 equations were significantly negatively correlated with the CI of Scott and Reinhardt (2001). These correlations progressively improved from $r = -0.30$ for equation 1 to $r = -0.60$ for equation 4, suggesting that as the relative weighting of SFL increases, the CFHI becomes a better predictor of crown fire propagation. This only occurs up to a weighting factor of 8, however, after which the closeness of the correlation declines.

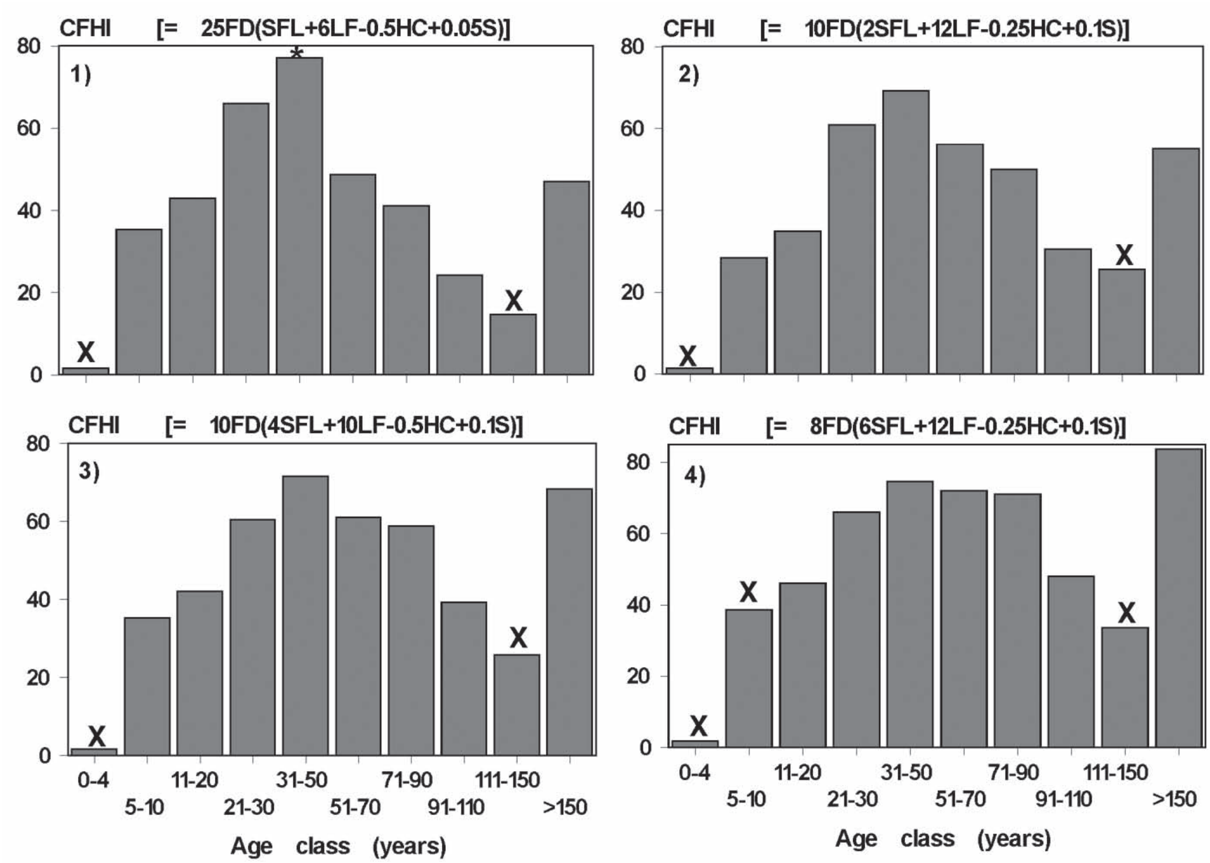

Figure 4—Average Crown Fire Hazard Indexes for different aged forests, calculated using four different CFHI equations and age class grouping F. * designates a CFHI which is significantly higher (P < 0.05) than that of old-growth. x designates a CFHI which is significantly lower (P < 0.05) than that of old-growth.

The CFHIs in figure 4 are shown only for one grouping of age classes as there were no substantial differences between the six different age groupings in the relative rankings of old-growth versus younger forests. The CFHI was always lowest for 0 to 5 year old age classes, then increased to peak values in 20 to 90 year old age classes, before declining in 100 to 150 year old age classes then rising again in old-growth. The CFHI for old-growth was lower than that of a younger age class forest for all equations in which SFL had a weighting factor < 5. However, it was statistically significantly lower (Kruskal Wallis tests, P = 0.05) only when the SFL weighting factor was < 2, as in equation 1 (figure 4). The CFHI for old-growth was also significantly higher than that for 0 to 4 and 111 to 150 year old stands (figure 4).

It can be concluded that whether or not younger forests have a higher crown fire hazard than old-growth in the study area depends primarily on the weighting given to surface fuel load. As the weighting given to this factor increases, the relative crown fire hazard of old-growth forests increases. However, as no reasonable equation could be found which resulted in old-growth forests having a statistically significantly higher crown fire hazard than all younger forests, it can also be concluded that simply clearcutting old-growth will not produce younger forests that always have a lower crown fire hazard than old-growth forests. Following clearcutting, fuel abatement treatments, such as slash reduction and thinning, would be necessary to significantly reduce crown fire hazards. Slash reduction would definitely be required to reduce post clearcutting surface fire hazard below that of old-growth forests. These conclusions are consistent with those of DellaSala and Frost (2001), who reported that old-growth forests in the western U.S. were less likely to burn catastrophically than younger forests.

Guidelines for fuel reduction treatments which lower fire hazards in forests are becoming available (for example, Keyes and O'Hara 2002; Peterson and others 2005). The present study suggests that both surface and crown fire hazard reduction would benefit from an emphasis on reducing surface fuels. However, the ecological benefits of surface fuels (Brown and others 2003; Feller 2003) as well as their influence on fire hazard must be considered.

Acknowledgments

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Evaluation of a Dynamic Load Transfer Function Using Grassland Curing Data

Patricia L. Andrews[1], Stuart A.J. Anderson[2], Wendy R. Anderson[3]

Abstract—*Understanding and calculating fire behaviour in various fuel types is essential for effective fire management, including wildfire suppression and fuels management. Fire spread in grassland fuel is affected by the curing level, the amount of dead fuel expressed as a percentage of the total (live and dead fuel combined). The influence of live fuel is included in various fire models in different ways. U.S. fire behavior prediction systems are based on Rothermel's fire spread model, which uses the load of live and dead fuel and the moisture content of each. Dynamic fuel models include a transfer of fuel load from the live to dead class as a function of live fuel moisture. Australian and New Zealand grassland fire behavior models rely heavily on the curing level as a major determinant of the ability for a fire to develop and spread, and place greater direct emphasis on both the proportion and moisture content of the dead fine fuels. A joint Australian and New Zealand study under the Australian Bushfire Cooperative Research Centre (CRC) is addressing various methods of assessing curing levels in grasslands. Data from that study are used to evaluate the dynamic fuel load transfer function used in fuel models developed for the Rothermel spread model. Results showed that live fuel moisture is not an indicator of level of curing. A significant difference is demonstrated in calculated rate of spread using the load transfer model versus direct entry of live fuel moisture and level of curing.*

Introduction

Fuels management planning often involves modeling potential fire behavior to identify areas of risk, assess hazard, and evaluate the effectiveness of various fuel treatment options. Fire behavior for a given fuel type can be modeled under a range of weather conditions and seasonal changes. Fire behavior modeling supports other aspects of fire management including suppression, prevention, and prescribed fire.

Fire behavior is influenced primarily by the fuel type (grass, shrub, etc.), fuel condition (moisture content, percentage of dead fuel), wind speed, and slope. The moisture content of fine dead fuel varies diurnally in response to changes in temperature, humidity, solar radiation, and rainfall. Live fuel moisture changes seasonally due to the physiology of the plant and its response to seasonal weather conditions. Seasonal curing of live herbaceous plants leads to a change in the ratio of dead to live material in the fuel complex, commonly referred to as level of curing. Live fuel plays an important role in determining the behavior of grassland fire (Cheney and Sullivan 1997, Cheney and others 1998). The level of curing has a major effect on grass fire behavior, in particular fire spread (Alexander 1993, Anderson and Pearce 2003).

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The influence of live fuel is incorporated into fire behavior models in several ways. The fire models used in New Zealand and Australia place the emphasis on level of curing, whereas U.S. models utilize live fuel moisture. New Zealand uses the Canadian grassland fire behavior models from the Canadian Fire Behavior Prediction System based on data collected in Australia (Forestry Canada Fire Danger Group 1992). There are models for cut or matted grass and for natural standing grass.

In Australia a fire model has been developed for grassland (three defined pasture types) by Cheney and others (1998) to replace existing models based on the McArthur Mark 3 and Mark 5 Fire Danger Meters (McArthur 1966, McArthur 1977) and provided in equation form by Noble and others (1980). Although the fire models used in New Zealand and Australia are quite different, they both predict fire spread in grasslands from fine dead fuel moisture, wind speed, and degree of curing.

Fire behavior prediction systems in the U.S. are based on Rothermel's (1972) surface fire spread model. Calculations are based on a description of the fuel, fuel moisture content of each size class of dead and live fuel, wind speed, and slope. The fire model itself does not include the influence of curing. Dynamic fuel models are used as a means of modeling changes in fire behavior that occur as herbaceous fuels cure and die.

In this paper we evaluate the dynamic load transfer function that is part of fuel models developed for use with Rothermel's surface fire spread model (Scott and Burgan 2005). We compare the load transfer model predictions with field sampled grassland curing data and we examine the influence of the load transfer function on rate of spread calculations.

Grassland Curing Study

Grassland curing data are being collected as part of an ongoing study under the Australian Bushfire Cooperative Research Centre (CRC): "Improved Methods for the Assessment and Prediction of Grassland Curing" (www.bushfirecrc.com). Grass curing describes the annual or seasonal cycle of grasses dying and drying out following flowering. Degree of curing refers to the proportion of cured (dead) material in grasslands, expressed as a percentage of the total grassland fuel complex (live and dead material). It is a critical input to grassland fire behavior and fire danger models used in Australia and New Zealand. Current curing inputs are often inaccurate, leading to incorrect determination of grassland fire danger levels and potential fire behavior. Many important fire management decisions and strategies are based upon this grassland fire behavior information, and fire managers need access to accurate and reliable information to protect life and property.

The degree of curing is currently assessed visually or by satellite remote sensing using an index based on the reflective properties of grasses at different wavelengths. Visual assessment is often inaccurate, sometimes differing vastly from the actual curing value obtained from destructive sampling. Problems include difficulties obtaining and extrapolating estimates over large areas, experience of observers, calibration of visual assessments, and timing and frequency of observations (Anderson 2005, Anderson and Pearce 2003, Millie and Adams 1999).

Remote sensing is used to assess curing levels in grasslands over parts of Australia (Paltridge and Barber 1988, Barber 1990, Allan and others 2003). However, the algorithms developed have had little validation outside of southern Australia, and there are issues with the accuracy of the technique due to atmospheric conditions and lack of uniformity of grasslands within pixels.

The Bushfire CRC project is examining improved remote sensing approaches, and will also include evaluation and modification of agricultural pasture growth models for curing determination. These models account for environmental and physiological factors regulating grass growth. An Australasian-wide field sampling program is providing data for development and validation of techniques. We used preliminary field data for this analysis.

Destructive sampling of grasses is the most accurate method of collecting curing data, but is not practical to implement on a large scale. It is labor-intensive to collect and process destructive samples, and there are further issues with obtaining spatially-representative samples of curing across the landscape.

Curing data in the CRC study were obtained by destructive field sampling. Sampling quadrats were located along two transects at right angles to each other and a total number of approximately five samples were collected. For each sample, all the vegetation from within a $0.25m^2$ frame was clipped with shears to the ground level and removed and placed in a bag. In the laboratory, the samples were then separated into live and dead material, oven dried at 100°C for 24 hours and then weighed. The degree of curing was then determined by calculating the percentage of dead material expressed as a percentage of the total (live and dead) material.

Samples of live, dead, and combined fuel moisture were also collected in the field, to investigate the feasibility of using grass fuel moisture data to calculate curing percentage, assuming that the moisture status of the grasses represents a live or dead state. Live and dead fuel moisture samples were collected randomly from within the curing sampling area, sealed in tins, weighed, oven-dried for 24 hours at 100°C and reweighed. The moisture content of the combined (live and dead) fuel was calculated using the material collected as part of the destructive sample from the $0.25m^2$ sampling frame. Collecting representative fuel moisture data in the field can be difficult. Live moisture varies by the part of the plant and the stage of growth as well as by grass species. For example on the same date and location Australian native grass may have a moisture content of 125% while improved pasture has a moisture content of 250%.

Table 1 shows the data from the grassland curing study used in this analysis. There are ten sites, three in New Zealand and seven in Australia. The type of grass and level of grazing is noted for each. The grass is characterized by loading and height. The date of each of the fourteen sample data points is given with the live fuel moisture and level of curing.

Dynamic Load Transfer Function

The dynamic load transfer function is part the of dynamic fuel models developed for use with Rothermel's (1972) surface fire spread model. Dynamic fuel models are used as a means of modeling changes in fire behavior that occur as herbaceous fuels cure and die. The fire model itself does not include the influence of curing. Calculations in Rothermel's fire model are based on fuel model, fuel moisture content of each size class of dead and live fuel, wind speed, and slope. A fuel model is a set of intrinsic fuel parameters that are required by the fire model.

Table 1—Data from the Australian Bushfire Cooperative Research Centre (CRC) study: "Improved Methods for the Assessment and Prediction of Grassland Curing."

	Site description				Sample data		
Location*	Grass type**	Grazing***	Total fuel load	Grass height	Date	Live fuel moisture content	Level of curing
			(ton/acre)	(ft)		- - - - - - - - -(%)	- - - - - - - - - -
Monaro	IP	UG	3.8	1.1	8/8/2005	211	93
Monaro	IP	UG	3.6	1.1	9/6/2005	270	91
Fisher	IP	LG	1.4	1.5	8/18/2005	315	87
Majura	IP	UG	1.5	2.3	1/16/2006	92	79
Majura	IP	UG	1.2	2.3	2/22/2006	113	71
Umbigong	NG	LG	2.2	0.8	8/30/2005	124	92
Tidbinbilla	IP	HG	0.6	0.7	1/24/2006	152	99
Braidwood	IP	LG	1.0	0.7	1/5/2006	142	80
Braidwood	IP	LG	0.7	0.7	2/14/2006	192	84
Milton	IP	UG	7.0		9/12/2005	331	72
Darfield	IP	LG	1.1	0.5	9/16/2005	292	58
Darfield	IP	LG	0.7	0.5	2/20/2006	320	86
Godley Head	IP/NG	UG	4.1	1.0	9/17/2005	234	80
Lake Lyndon	IP/NG	UG	2.3	0.8	2/14/2006	165	70

*Darfield, Godley Head, and Lake Lyndon are in New Zealand; the rest are in Australia.
**IP = Improved Pasture; NG = Native Grass.
***UG = Ungrazed; LG = Lightly Grazed; HG = Heavily Grazed.

The standard set of 13 fire behavior fuel models, which has been widely used since 1976, are static; fuel model parameters do not change (Albini 1976, Anderson 1982). Dynamic fuel models, on the other hand, include the dynamic load transfer function which changes the fuel description by moving some of the load from the live category to dead. Although rarely used, the option of developing dynamic custom fuel models was available in the BEHAVE fire behavior prediction and fuel modeling system (Burgan and Rothermel 1984). Seventeen of the recently developed set of 40 standard fuel models are dynamic (Scott and Burgan 2005). These 40 fuel models were designed to represent a wider range of fuel types than the set of 13, and have been implemented in the BehavePlus fire modeling system (Andrews and others 2004), the FARSITE fire area simulator (Finney 1998), and other fire behavior prediction systems in the U.S.

The dynamic fuel load transfer function is shown in figure 1. Load is transferred from the live herbaceous class to dead as a function of live fuel moisture. The same relationship is used for all dynamic fuel models.

- For live herbaceous fuel moisture content of 120 percent or higher, most of the herbaceous fuels are assumed to be green, and the initial live herbaceous load for the fuel model stays in the live category.
- For live fuel moisture of 30 percent or lower, the herbaceous fuels are considered fully cured, and all live herbaceous load is transferred to the dead category.
- For live fuel moisture between 30 and 120 percent, part of the live herbaceous load is transferred to dead. For example, if live fuel moisture is 75 percent (halfway between 30 and 120 percent), half of the initial live herbaceous load is transferred to dead herbaceous, the remainder stays in the live herbaceous class.

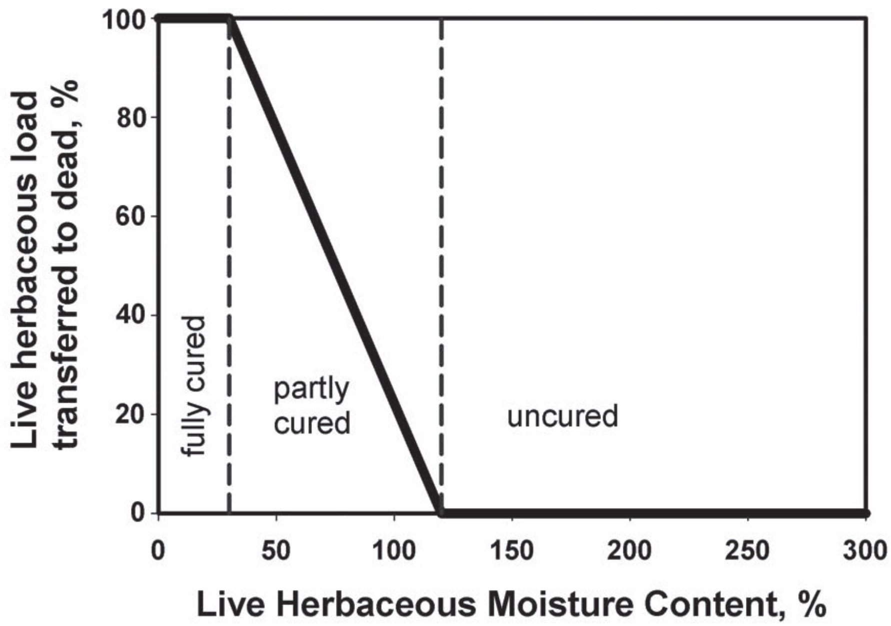

Figure 1—Percent of the live herbaceous fuel load that is transferred to the dead category (Burgan 1979). There is dead fuel in the fuel model when the percent is zero, for the section of the graph labeled "uncured."

Table 2 gives the parameters for the standard fire behavior fuel models applicable to grasses. Fuel models 1, 2, and 3 are from the original set of 13 and are static. Fuel models GR1 through GR9 are dynamic fuel models from the set of 40. The listed fuel loadings for the dynamic fuel models are the values before the fuel load transfer function is applied. The percentage of the total load that is dead fuel prior to load transfer is also given on the table. Scott and Burgan (2005) refer to the percent load transferred as *curing percent*, and say that the parameters on the table are for *uncured* fuel. There is, however, dead fuel in the fuel models even before any load is transferred from live to dead. As an illustration of the difference between percent load transferred and percent dead, table 2 gives the percent dead at 50 percent load transferred. Fuel model GR2 is 63 percent dead (63 percent cured) when 50 percent of the load is transferred from live to dead. In Australasian and Canadian fire behaviour models, degree of curing in grasslands is defined as percent dead. For this paper, we use the terminology "percent load transferred" where Scott and Burgan used the term "percent cured".

As an illustration of the effect of live fuel moisture for static and dynamic fuel models, the BehavePlus fire modeling system was used to compare calculated rate of spread using Rothermel's fire spread model for seven fuel models under the same wind and fuel moisture conditions (5 percent dead fuel moisture, 5 mi/h wind, no slope) (figure 2). Fuel models 1 and 3 have no live fuel, so rate of spread is not affected by a change in live fuel moisture. Fuel model 2 is a static model with a live fuel component. The effect of live fuel moisture is therefore limited to the relationships in the original formulation of the Rothermel (1972) fire model. Fuel models GR1, GR2, GR4, and GR7 are dynamic. Live fuel moisture is not only used in the rate of spread

Table 2—Load and depth for grass fire behavior fuel models. Percent dead for no load transfer and for 50% load transfer from live herbaceous to dead are given to illustrate the difference between percent load transferred and percent dead.

Fuel model		Fuel model parameters: Fuel load (ton/ac) 1-h	10-h	100-h	live herb	Depth (ft)	Percent dead fuel prior to load transfer	Percent dead at 50% load transfer
1	Short Grass	0.74				1.0	N/A	N/A
2	Grass and timber understory	2.0	1.0	0.5	0.5	1.0	N/A	N/A
3	Tall Grass	3.0				2.5	N/A	N/A
GR1	Short, Sparse, Dry climate	0.1			0.3	0.4	25.0	63
GR2	Low Load, Dry Climate	0.1			1.0	1.0	9.1	55
GR3	Low Load, Very Coarse, Humid Climate	0.1	0.4		1.5	2.0	6.3	63
GR4	Moderate Load, Dry Climate	0.25			1.9	2.0	11.6	56
GR5	Low Load, Humid Climate	0.4			2.5	1.5	13.8	57
GR6	Moderate Load, Humid Climate	0.1			3.4	1.5	2.9	51
GR7	High Load, Dry Climate	1.0			5.4	3.0	15.6	58
GR8	High Load, Very Coarse, Humid Climate	0.5	1.0		7.3	4.0	6.4	59
GR9	Very High Load, Humid Climate	1.0	1.0		9.0	5.0	10.0	59

calculations according to the fire spread model, but also to change the fuel model according to the fuel load transfer function. For fuel model GR7 under the specified dead moisture and wind conditions, there is a four-fold increase in calculated rate of spread as live fuel moisture decreases from 100 to 75 percent; and rate of spread increases by a factor of 2.4 for the very small change in live fuel moisture from 100 to 95 percent. In his paper "Sensitivity of a fire behavior model to changes in live fuel moisture" Jolly (2005) found that the grass fuel models within the set of 40 new fuels showed the highest sensitivity to live fuel moisture changes. They were most sensitive to changes in live fuel moisture from 90 to 100%.

The fuel load transfer function was developed as part of a live fuel moisture model developed by Burgan (1979) for use in the U.S. National Fire Danger Rating System (Deeming and others 1977). The load transfer function is a conceptual model; development was not based on live fuel moisture and

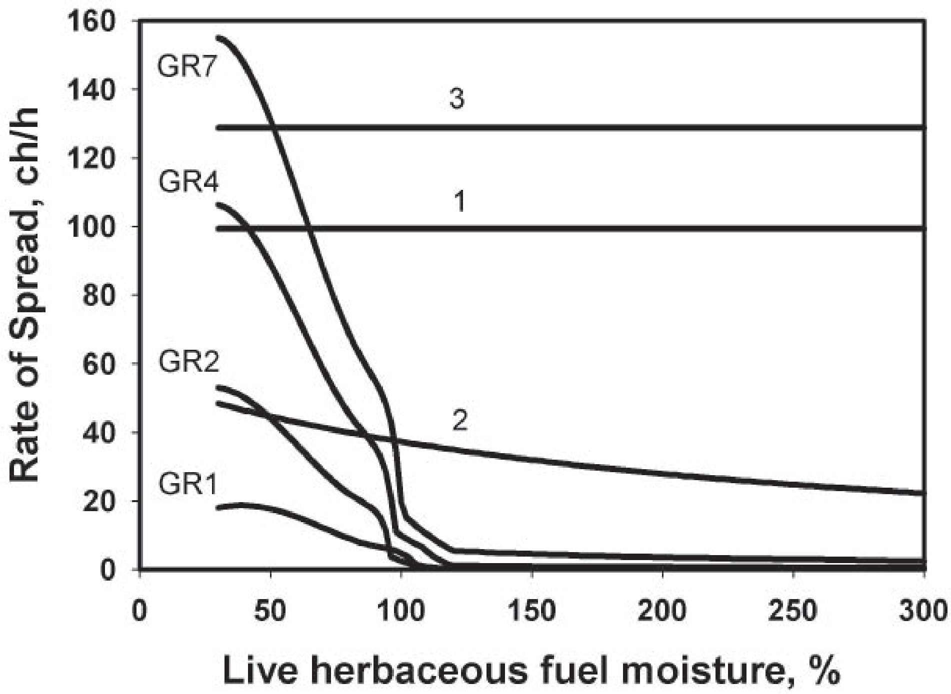

Figure 2—Comparison of calculated rate of spread for seven fuel models to illustrate sensitivity to live fuel moisture for static (1, 2, 3) and dynamic (GR1, GR2, GR4, GR7) fuel models. Dynamic fuel models include the use of the load transfer function.

curing data. The live fuel moisture range of 30 to 120 percent was defined as the transition stage because 120 percent "roughly defines the moisture content at which new growth is complete and the foliage is mature." Thirty percent was defined as the minimum moisture for transition because "that is the approximate fiber saturation point, below which plants are assumed to be dead." The fuel load transfer function has not previously been evaluated using field data.

Results

Table 3 gives the sample data for live fuel moisture and level of curing, and the model values for percent load transferred and percent dead calculated from the sampled live fuel moisture. We compare the sampled and modeled level of curing (percent dead). A fuel model was assigned to each sample site based primarily on the fuel loadings of the sample data in table 1. The Milton site in coastal Australia was the only one designated as humid. Only three of the fourteen sample points had live fuel moisture content below 120 percent. According to the dynamic fuel load transfer function, moisture above 120 percent indicates no load is transferred from live to dead. The modeled percent dead for the fuel models is calculated from the percent dead for the fuel model before the load transfer (see table 2) and the percent transferred from live to dead according to the dynamic load transfer function.

Table 3—Fuel models were assigned to each site primarily based on fuel loading. Field data includes live fuel moisture and level of curing (percent dead). The fuel load transfer function is used to calculate percent load transferred for the associated live fuel moisture value. Percent dead is affected by the fuel model (see table 2).

		Sample data		Model values	
Location	**Fuel model**	**Live fuel moisture content**	**Level of curing**	**Percent load transferred live to dead**	**Percent dead**
		- - - - - - - - - (%) - - - - - - - - -			
Monaro	GR7	211	93	0	15.6
Monaro	GR7	270	91	0	15.6
Fisher	GR4	315	87	0	11.6
Majura	GR4	92	79	34.5	42.1
Majura	GR4	113	71	12.1	22.3
Umbigong	GR4	124	92	0.5	12.0
Tidbinbilla	GR1	152	99	0	25.0
Braidwood	GR1	142	80	0	25.0
Braidwood	GR1	192	84	0	25.0
Milton	GR8	331	72	0	6.4
Darfield	GR2	292	58	0	9.1
Darfield	GR2	320	86	0	9.1
Godley Head	GR7	234	80	0	15.6
Lake Lyndon	GR4	165	70	0	11.6

Figure 3 is a plot of the sample data, level of curing (percent dead) vs. live fuel moisture, with an indication of the assigned fuel model. The dynamic fuel load transfer function is used to plot percent dead for each fuel model. Figure 4 is a plot of predicted and observed level of curing (percent dead). The lowest observed curing level was 58 percent while the highest predicted value was 42 percent. A simple look at the plots precludes the need for a statistical analysis.

The load transfer function is based on the assumption that fuel is "uncured" when live fuel moisture is over 120 percent. Note that a significant amount of the grass fuel load is dead at high live fuel moisture values. For example, the live fuel moisture content was 315 percent for the Fisher site, corresponding to a measured 87 percent curing level. The load transfer function gives no load transfer and 11.6 percent dead fuel for fuel model GR4 and live fuel moisture 315 percent.

It is apparent that there is no useful relationship between live fuel moisture and curing level for this data. We conclude that for this data set, live fuel moisture is not an indicator of level of curing.

Influence on Rate of Spread Calculations

The dynamic load transfer model is an intrinsic part of dynamic fuel models. Given that we have shown that live fuel moisture may not be an indicator of curing, we examine the option of independent specification of live fuel moisture and curing level.

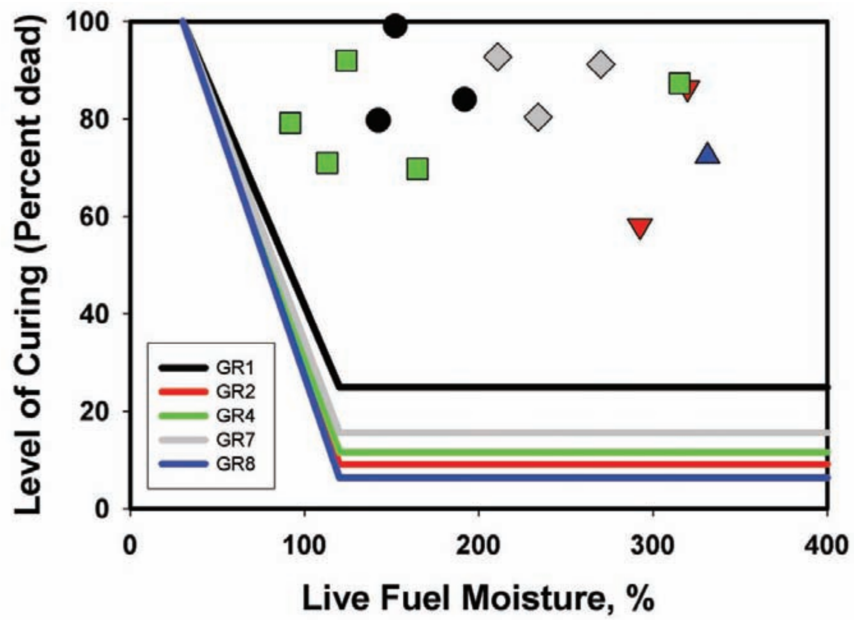

Figure 3—Australian and New Zealand live fuel moisture and curing data compared to the dynamic load transfer function. There is a different curve for each fuel model because of the dead fuel in the fuel models when there is zero load transferred from live to dead. The sample data points are from table 3.

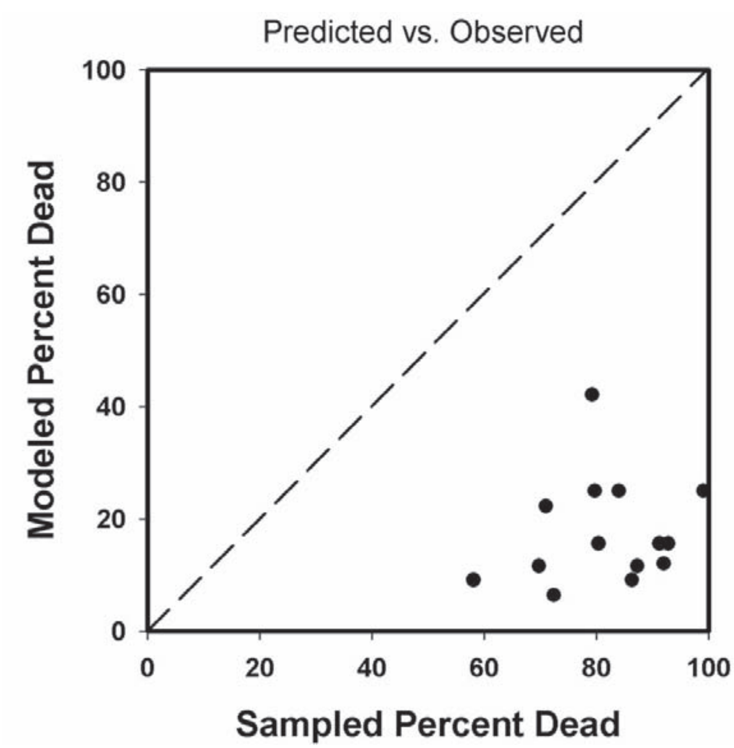

Figure 4—Predicted vs. observed level of curing (percent dead). Data are from table 3.

As a means of dealing with the required relationship between curing and live fuel moisture, Scott and Burgan (2005) give the following guidance in use of the dynamic fuel models: "It will often be preferable to estimate live herbaceous moisture content by working backward from observed or estimated degree of herbaceous curing. For example, if the fuelbed is observed to be 50 percent cured, use a value of 75 percent for live herbaceous moisture content." A user who knows both live fuel moisture and curing level must choose which to use. It is not possible, for example, under the current formulation, to calculate rate of spread for live fuel moisture of 200 percent and 50 percent cured. (Recall that Scott and Burgan use the term percent cured for the percent load transferred from live to dead rather than the percent dead.)

Table 4 shows the live fuel moisture values that correspond to 100, 75, 50, 25, and 0 percent load transferred according to the function. The calculated rate of spread for fuel model GR4 (5 percent dead fuel moisture, 5 mi/h wind, and no slope) is given for each and indicated on the curve in figure 5. For example, live fuel moisture of 75 percent and a 50 percent load transfer gives rate of spread of 53 ch/h. These calculations are as implemented in the BehavePlus fire modeling system using the dynamic fuel models as described by Scott and Burgan.

Consider the effect of not using the dynamic load transfer function, but rather directly supplying values for live fuel moisture and load transfer percent. Table 5 shows calculated rate of spread for a range of live fuel moisture values and load transfer levels. The highlighted values in table 5 correspond to those in table 4 and are indicated on figures 6 and 7. Figure 6 is rate of spread for five levels of load transfer for a range of live fuel moisture. The curves in figure 6 correspond to the columns in table 5. For a fixed load transfer of 50 percent, live fuel moisture from 30 to 300 percent results in rate of spread from 11 to 90 ch/h. Similarly, figure 7 is rate of spread for seven levels of live fuel moisture for a range of load transfer values. The curves in figure 7 correspond to the rows in table 5. For a fixed live fuel moisture of 75 percent, load transfer from 0 to 100 percent results in rate of spread from 2 to 110 ch/h. There is a significant difference between the results using the dynamic load transfer function and specifying live fuel moisture and curing independently.

Table 4—Live fuel moisture and percent load transferred from live to dead according to the dynamic load transfer function. Associated calculated rate of spread for fuel model GR4, 5 percent dead fuel moisture, 5 mi/h midflame wind, and no slope. The five highlighted rate of spread values are shown in figure 5.

Live fuel moisture	Load transferred live to dead*	Rate of spread
(%)	(%)	*(ch/h)*
30	100	**110**
53	75	**87**
75	50	**53**
98	25	**11**
120	0	**1**
200	0	1
300	0	1

*Referred to as percent cured by Scott and Burgan (2005).

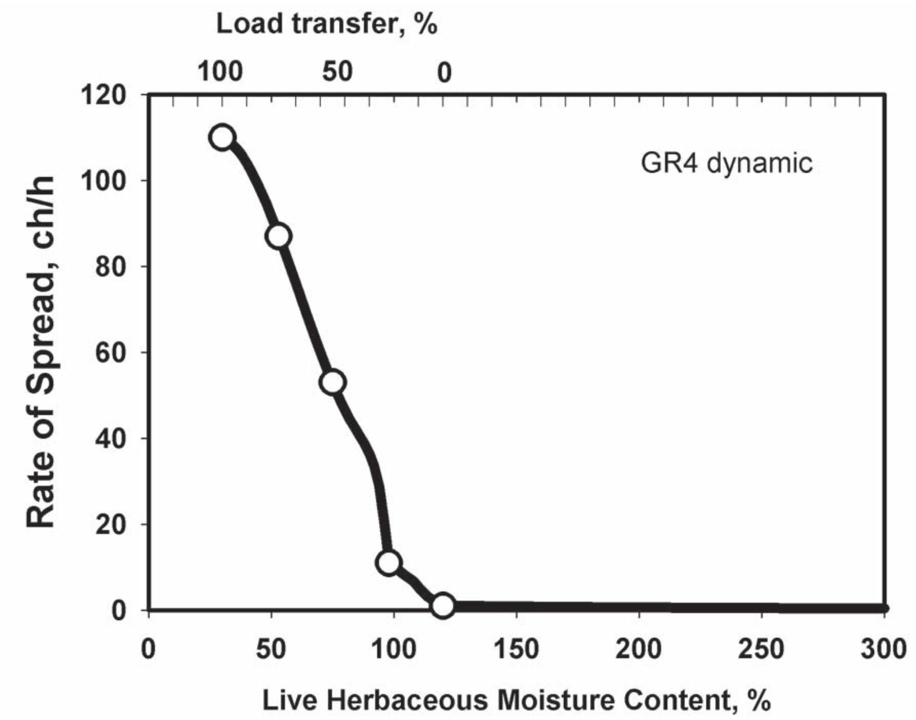

Figure 5—Calculated rate of spread for dynamic fuel model GR4, which incorporates the fuel load transfer function. Load is transferred from the live to the dead class as a function of live fuel moisture. The data points on the curve are given in table 4.

Table 5—Calculated rate of spread for a range of live fuel moisture and load transfer values. The highlighted values correspond to those in table 4 and are plotted on the curves in figures 6 and 7. The curves in figure 6 correspond to the columns of this table. The curves in figure 7 correspond to the rows.

Live herbaceous moisture (%)	Rate of spread (ch/h) Load transferred from live to dead*, %				
	100	75	50	25	0
30	**110**	103	90	69	3
53	110	**87**	66	49	2
75	110	76	**53**	33	2
98	110	66	44	**11**	1
120	110	59	38	10	**1**
200	110	43	24	6	1
300	110	32	11	5	1

*Referred to as percent cured by Scott and Burgan (2005)

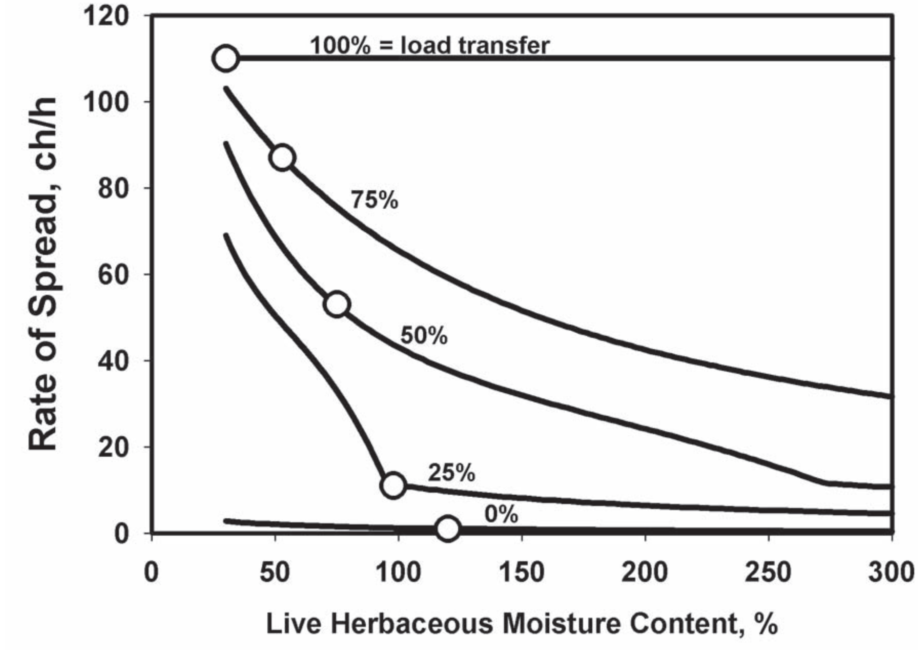

Figure 6—Rate of spread is calculated for several levels of load transfer for a range of live fuel moisture. Use of the load transfer function results in only the single indicated point on each curve. The curves correspond to the columns in table 5.

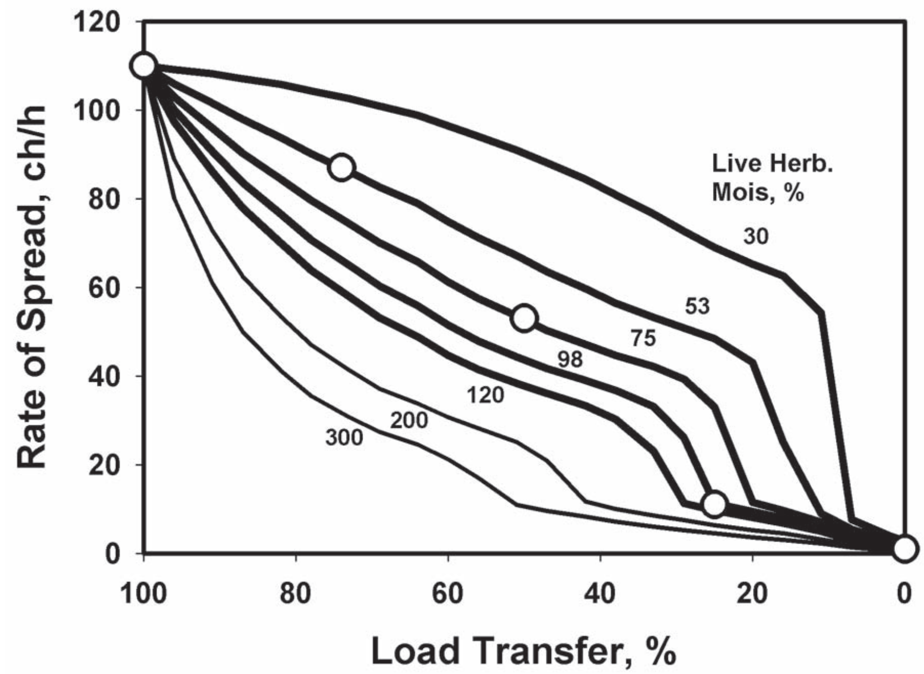

Figure 7—Rate of spread is calculated for several values of live herbaceous moisture for a range of load transfer percentage. Use of the load transfer function results in only the single indicated point on each curve. The curves correspond to the rows in table 5.

Discussion

It is recognized that curing level is an important factor in determining fire behavior in grass fuel types. Because the Rothermel (1972) fire spread model does not include the influence of curing, fuel models that incorporate a dynamic load transfer function have been developed by Scott and Burgan (2005) to reflect seasonal curing. Live fuel moisture is used to estimate the load that is transferred from the live to dead class in the fuel model. Evaluation of the dynamic load transfer function using field sampled data from Australia and New Zealand showed that the assumption that level of curing is related to live fuel moisture needs to be questioned.

An examination of the use of the dynamic load transfer function compared to the option of independent specification of live fuel moisture and curing level showed a significant difference in rate of spread calculations using Rothermel's model. Although both live fuel moisture and degree of curing are currently difficult to determine, we suggest that the required use of the dynamic load transfer function be reconsidered in anticipation of improved models and methods of assessment.

There is a need for longer term research on the curing process, a description of the seasonal changes in the grasslands for fire modeling, and on the combustion processes involved in the burning of a mixture of live and dead fuel. It is imperative that fire researchers and fire managers continue to question, validate, and refine fire behavior models and their underlying assumptions for effective fire and fuel management.

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Foliar Moisture Contents of North American Conifers

Christopher R. Keyes[1]

Abstract—*Foliar moisture content (FMC) is a primary factor in the canopy ignition process as surface fire transitions to crown fire. In combination with measured stand data and assumed environmental conditions, reasonable estimates of foliar moisture content are necessary to determine and justify silvicultural targets for canopy fuels management strategies. FMC values reported in research publications are best used for this purpose. This paper summarizes the results of 11 studies on the FMC values and trends for 16 North American conifers. FMC values ranged from 73 to 480 percent but varied by species, foliage age, and season. FMC values presented here and the references associated with them will be helpful to managers engaging in canopy fuels planning with the use of popular fire behavior and fuels management software (e.g. NEXUS, Fuels Management Analyst, and the Forest Vegetation Simulator's Fire and Fuels Extension).*

Keywords: *crown fire, fire surrogates, wildfire hazard, canopy ignition, shaded fuelbreak*

Introduction

The relationship of stand structure to fire behavior, and the basis for silviculturally modifying stands to reduce crown fire susceptibility, have been well established (Graham et al. 2004, Agee and Skinner 2005). In planning silvicultural treatments to achieve crown fire resistance, assumptions must be made about uncontrolled parameters that are beyond the scope of manipulation (Keyes and O'Hara 2002). One of these is the percent foliar moisture content (FMC) of overstory and midstory trees.

The quantitative basis for prescribing silvicultural treatments (such as thinning and pruning) to the aerial fuel complex is Van Wagner's (1977) model of the relationships among crown fire behavior, surface fire behavior, and canopy fuel structure. Since its inception as a tool to predict the occurrence and behavior of crown fires, Van Wagner's model has since been refined and adapted in formats useful for fuels planning (Alexander 1988, Scott and Reinhardt 2001, Keyes and O'Hara 2002). It is currently utilized by virtually all decision-support software currently used in fuels planning in North America, including FARSITE (Finney 1998), NEXUS (Scott 1999), the CrownMass program of the Fuels Management Analyst tool suite (Fire Program Solutions 2003), and the Forest Vegetation Simulator's (FVS) Fire and Fuels Extension (Reinhardt and Crookston 2003).

Using one or more of those simulation programs, fuels planners identify structural targets that can reduce a stand's susceptibility to crown fire initiation, crown fire spread, or both, and then propose fuels treatments to achieve these targets. Ideally, the effects of proposed silvicultural fuels treatments on fuel dynamics are also considered (Keyes and Varner 2006). To decrease

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susceptibility to torching or canopy ignition, a target canopy base height is determined on the basis of anticipated surface fireline intensity and foliar moisture content. For the former parameter, measured surface fuelbed properties are utilized in combination with a worst-case fire weather scenario to determine the most intense surface fire behavior that is likely to occur. But fuels planners lack a standard basis for determining appropriate values for FMC. This paper reviews relevant literature to address that need.

Variability in Foliar Moisture Content

Fuels treatments are expected to be effective over a range of temporally changing conditions, so estimates of FMC are best drawn from published studies that document changes in foliar moisture content over seasons or years. A list of these is given in table 1 for 16 common North American conifer species. The table reveals a wide range of moisture content values based on species, period of measurement, and foliage age. These values are drawn from the primary literature; in some cases values have been visually approximated to the nearest 5 percent from published graphs.

Table 1—Published percent foliar moisture content (FMC) values for North America forest conifers. In some cases values are visually approximated to the nearest 5 percent from graphs.

Species	New foliage[1]	Old foliage[2]	Period[3]	Reference
Abies balsamea – balsam fir	180-230	130-150	Jul-Sep	Kozlowski and Clausen 1965
	130-220	110-150	Jul-Oc	Little 1970t
	143-356	75-140	Jan-Dec	Chrosciewicz 1986
Abies grandis – grand fir	167-313	112-138	Jun-Oct	Agee et al. 2002[4]
	140-310	110-150	Jun-Sep	Agee et al. 2002[4]
Abies lasiocarpa – subalpine fir	150-225	110-125	Aug-Sep	Agee et al. 2002[4]
	115-312	—	Jun-Sep	Agee et al. 2002[4]
Abies magnifica var. *shastensis* – Shasta red fir	170-310	—	Jun-Sep	Agee et al. 2002
Picea glauca – white spruce	146-480	78-139	Jan-Dec	Chrosciewicz 1986
Picea engelmanii – Engelmann spruce	(mixed	100-130)	Jul-Oct	Gary 1971
Picea mariana – black spruce	131-349	73-126	Jan-Dec	Chrosciewicz 1986
	—	75-115	Jan-Dec	Springer and Van Wagner 1984
Pinus banksiana – jack pine	130-190	105-120	Jul-Oct	Johnson 1966
	137-288	79-129	Jan-Dec	Chrosciewicz 1986
Pinus clausa – sand pine	195-210	145-150	Jul-Oct	Hough 1973
Pinus contorta – lodgepole pine	117-148	96-118	Late Aug	Hartford and Rothermel 1991
Pinus edulis – pinyon pine	(mixed	95-130)	Jul-Oct	Jameson 1966
Pinus ponderosa – ponderosa pine	125-210	95-115	Jul-Oct	Philpot and Mutch 1971
	149-275	85-120	Jun-Oct	Agee et al. 2002[4]
	115-340	85-135	Jun-Sep	Agee et al. 2002[4]
Pinus resinosa – red pine	160-250	120-140	Jul-Sep	Kozlowski and Clausen 1965
	135-200	110-130	Jul-Oct	Johnson 1966
Pinus strobus – eastern white pine	150-230	130-140	Jul-Sep	Kozlowski and Clausen 1965
Pseudotsuga menziesii – Douglas-fir	120-200	80-120	Jul-Oct	Philpot and Mutch 1971
Tsuga canadensis – eastern hemlock	170-280	120-150	Jul-Sep	Kozlowski and Clausen 1965

[1]Range of percent FMC values for first-year leaves.
[2]Range of percent FMC values for second-year leaves or older.
[3]Month(s) comprising the study duration.
[4]Two separate studies for each species in same publication.

Foliar moisture content varies seasonally. Lowest foliar moisture contents typically occurring during late spring (Philpot and Mutch 1971), rapidly increase to an annual maximum shortly therafter, and then steadily decline through summer to fall (Kozlowski and Clausen 1965). This trend is physiologically based, and is more a function of the leaf's changing carbohydrate content than its water content. For example, an analysis of young red pine (*Pinus resinosa*) foliage revealed a seasonally declining FMC even as the actual water content increased (Kozlowski and Clausen 1965).

Like other fuel properties, the moisture content of foliage also varies on a diurnal basis. Philpot's (1965) study of ponderosa pine (*Pinus ponderosa*) summertime FMC revealed diurnal fluxes of 26 to 34 percent. FMC roughly tracked ambient relative humidity measured over the same period. More modest fluxes of 4 to 12 percent for ponderosa pine, Douglas-fir (*Pseudotsuga menziesii*), and grand fir (*Abies grandis*) were observed during a late August day in Washington by Agee et al. (2002).

The occurrence of worst-case fire weather and lowest foliar moisture content are usually asynchronous. For conifers such as ponderosa pine and Douglas-fir, old foliage FMC drops below 100 percent, but generally ranges between 100 percent and 130 percent during the summer months when ignitions are most frequent and fires most intense. In fuels planning, assumed FMC values should be kept seasonally consistent with the fire weather scenario used to predict surface fireline intensity.

Foliage age is another primary determinant of variation in FMC. Moisture content of first-year leaves is typically higher than older leaves by a substantial margin. For the species in table 1, the range of FMC values for new foliage is 120 to 480 percent, versus a range of 73 to 150 percent for older foliage (2^{nd} year or later). In a study of eastern white pine (*Pinus strobus*), FMC values between July and September ranged from 130 to 140 percent for old foliage, but ranged from 150 to 230 percent for new foliage on the same trees (Kozlowski and Clausen 1965). Although studies have identified FMC differences in foliage age, none have demonstrated FMC differences in tree age. Until this relationship is further examined, values in Table 1 should be applied regardless of stand or cohort age.

No reports have addressed FMC among stands of variable densities or other attributes of stand structure. Therefore, fuels planners must assume that stand structure or treatment history has no bearing on the FMC assumption. Differences between species and regions are apparent (table 1), but not with any obvious relationships to shade tolerance, latitude, or other useful ordinal characterizations that might suggest a need for regionally explicit assumptions, or that would allow extrapolation to other species not represented in table 1.

The case of mixed-species stands introduces additional complexity. In stratified even-aged mixtures or mixed multi-cohort stands, it is most appropriate to use the FMC value of the species relegated to the lower-most stratum (the stratum that will initiate the crown ignition process). For unstratified even-aged mixtures, it is suggested that the lowest FMC value be adopted among those species constituting at least 10 percent the stand's basal area.

Conclusion

Whenever possible, all assumptions in silvicultural fuels management should be supported on the basis of best available scientific information.

The foliar moisture content values summarized here should be utilized in the fuels planning process, and their supporting documentation cited in justifying silvicultural treatments of forest fuels. Alexander (1988) lists several additional studies of FMC that are more obscure but that could also prove useful. For species lacking published FMC data, a low default value of 90 or 100 percent is a prudently conservative assumption (e.g. Scott 2003). For this review, additional details that are present in the original research (table 1) were by necessity omitted in order to present all species together in one common tabular format. Additional information beyond the values presented here is available from the primary literature, and should be consulted and cited as necessary to establish the scientific basis for value assumptions used in fuels planning.

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Mapping the Relationship Between Wildfire and Poverty

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Abstract*—Wildfires and related government roles and responsibilities for federal wildland management are prominent in our national consciousness because of the increased severity in the last decade of fires on and around public lands. In recent years, laws, strategies, and implementation documents have been issued to direct federal efforts for wildfire prevention, firefighting, and recovery. Reliable national-level information and monitoring are essential to ensure good decision-making and agency accountability. Social and economic information about communities at risk from wildfire is critical to these decisions. Despite the indispensable nature of this information for understanding communities, wildfire risk, and cooperative efforts, there is a void in policy direction within the federal agencies to collect, understand, and use social and economic information in wildfire management programs. This study addresses community capacity and examines socioeconomic indicators as elements of wildfire risk. The study investigates whether communities most at risk from wildfire are able to access and benefit from federal programs established to serve these communities. In other words, are the dollars, assistance, and fuels-reduction projects hitting the ground in the areas throughout the country that are most at risk to wildfire? This presentation will provide a forum to discuss the needs of rural and underserved communities in relationship to fire and fuels management programs.*

Introduction

Wildfires and the related government roles and responsibilities for federal wildland management are prominent in our national consciousness because of the increased severity in the last decade of fires on and around public lands. In recent years, numerous laws, strategies, and implementation documents have been issued to direct federal efforts for wildfire prevention, firefighting, and recovery. Reliable national-level information and monitoring are essential to ensure good decision-making and agency accountability.

Social and economic information about communities at risk from wildfire is critical to these decisions. Despite the indispensable nature of this information for understanding communities, wildfire risk, and cooperative efforts, there is a void in policy direction within the federal agencies to collect, understand, and utilize social and economic information in wildfire management programs.

This research project uses the concept of community capacity – a community's ability to protect itself, respond to, and recover from wildfire – and examines socioeconomic indicators (one component of community capacity) as elements of wildfire risk. Utilizing socioeconomic information, as well as ecological factors, this study set out to investigate, through a geographical-information-systems approach, whether communities most at risk from

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wildfire are able to access and benefit from federal programs established to serve these communities. In other words, are the dollars, assistance, and fuels-reduction projects hitting the ground in the areas throughout the country that are most at risk?

This research project found that federal agencies do not have the information and data necessary to answer this question. Spatial data to inform every aspect of this research – including data regarding the ecological conditions of federal lands, wildfire protection capability in and around communities, and the federal expenditures under the national fire plan – are unavailable and/or inadequate.

Using the limited data that are currently available, this research focused primarily on the relationship between poverty and populated areas at risk to wildfire. Our research indicates that there is a relationship between poverty and federal land ownership, and that more poor households are located in close proximity to federal lands. Perhaps more significant, the research shows a higher percentage of poor households in inhabited wildland areas that are not considered part of the Wildland Urban Interface – the areas that federal agencies and Congress have prioritized to receive the majority of funds for activities under the national fire plan. The research also indicates that, in the one state analyzed, poor households are more likely in areas with low or no fire response capabilities than are non poor households.

This research should be seen as a first step to document the importance of social and economic information and community capacity in wildfire policy and implementation. The lack of information about wildfire risk, including ecological conditions, socioeconomic indicators, and resource allocation convinced us to focus our recommendations on improving federal agency understanding and use of social and economic factors through national inventory and monitoring efforts. Specific recommendations include developing a method for measuring community capacity in the context of wildfire and using this methodology to redefine the concept of risk for implementation priorities at the national level and in state, regional, and local planning and risk assessment. Federal land management agencies must also improve systems for monitoring national fire plan expenditures and the datasets that support the prioritization of these funds.

Understanding the social and economic dynamics of communities is critical for providing federal assistance that will help communities protect themselves from wildfire and respond to and recover from an event. We encourage others to build on this effort to understand the complex social, economic, and ecological factors that influence wildfire risk. Specifically, we encourage federal agencies to take steps to understand the social and economic indicators that are necessary to understand and serve our nation's communities.

Research Methods

This study examines the relationship between wildfire and community risk through the concept of community capacity. The research also attempted to analyze federal resource allocation in conjunction with data indicating relative risk. To examine these issues, the project team conducted background research to identify indicators and nationally consistent data for each element of the project. The team also facilitated internal and external data review, mapped indicators once data had been collected, and reexamined and reported findings through the mapping process.

To illustrate the study elements, we sought data to use as indicators of community capacity and wildfire risk. This process was iterative, investigating potential datasets, summarizing the benefits and drawbacks of each, and obtaining feedback from an advisory committee. We also presented preliminary findings of the study at two community meetings in southern Oregon and central Oregon.

This section provides a description of the data we initially sought to examine community capacity, wildfire risk, and federal resource allocation. It includes the limitations of the best available data, and a summary of how we use the data in this study.

National-Level Data

This report is a national-level analysis that seeks to provide information on a national scale. The spatial information included in this report is provided at the county and census-block levels. Therefore, the visual analysis is, in many cases, more meaningful on a state level. Consequently, the researchers have included more detailed maps and analysis for the states of Washington and Oregon, as state-level examples. The maps and analysis shown for these two states are also available, upon request, for other states.

Identifying indicators that provide consistent and meaningful information for a nationwide study became the first challenge. Although some poverty data exist on a national scale (from the Census and Department of Housing and Urban Development), it was more difficult to find consistent national data on community capacity, protection capacity, wildfire risk, and federal resource allocation. The researchers encountered major challenges in finding spatial data, especially in a format conducive to national-level modeling. Specifically, there is a lack of suitable data in the areas of: (1) community capacity/protection capability (2) ecological conditions on federal lands/populated areas at risk from wildfire; and, (3) federal resource allocation.

Indicators and Data

The following section provides information about the purpose of each indicator, the data initially sought, the limitations encountered, and the data ultimately selected.

Community Capacity

Examining community capacity requires understanding a complex set of issues and indicators that are not easily summarized by a single set of data. Below, we explain the purpose for using the concept of community capacity, existing definitions of community capacity found in published research, the limitations we encountered in identifying data, and the indicators we ultimately chose for this research.

Community capacity can be used to assess the relative risk that a community faces from wildfire. Well defined, community capacity will provide the social information to tell us which communities are at a greater risk—less ready to protect themselves from wildfire, and less able to recover from the impacts of a fire. Understanding the capacity of a community to address the economic, social, and environmental costs of wildfire will lead to more directed policies and programs and a more efficient use of resources. Following are two definitions of capacity that we used to help frame the study and the indicators we sought to use for the research.

- Kusel (1996) defines community capacity as "the collective ability of residents to respond…to external and internal stresses; to create and take advantage of opportunities; and to meet the needs of residents, diversely defined."
- A response by American Forests to the 2001 Federal Register notice *Urban Wildland Interface Communities within the Vicinity of Federal Lands that are at High Risk from Wildfire*, defines community capacity as the collective ability of residents in a community to respond to external and internal stresses, to create and take advantage of opportunities, and to meet local needs. Community capacity in relation to wildfire addresses a community's ability to mitigate wildfire threats, respond to active wildfire, and mitigate post fire damage. This includes the ability to implement risk-reduction strategies, including hazardous fuels reduction, firefighting, and restoration activities (American Forests 2001).

For purposes of this research (and because of limited data), two indicators were used as a first step to measure community capacity as it relates to wildfire: (1) socioeconomic elements that influence a community's ability to respond to and recover from wildfire and (2) protection capability - systems that are in place that influence a community's ability to protect itself from an actual wildfire. As previously stated, a true assessment of community capacity would include a much broader array of social and cultural information; however, this information was not readily available at the time that this research was undertaken.

The study uses 2003 Housing and Urban Development (HUD) Income Limits, at a comparable census block group level, as the primary layer for poverty. HUD Income Limits reflect income, earnings and employment, and housing affordability. The Median Family Income Limit estimates are based on the U.S. Census Bureau median family income estimates with an adjustment using a combination of earnings and employment data, median family income data, and fair market rents. Data are available nationally. HUD Income Limits describe family sizes of one to eight persons, and a formula is provided to calculate income limits for larger family sizes. Income limits are adjusted for family size and areas with unusually high or low family income or housing-cost-to-income relationships (Housing and Urban Development). Income limit groups include families whose incomes do not exceed 80 percent of the median family income for the area *(low-income)*, families whose incomes do not exceed 50 percent of the median family income for the area *(very low-income)*, and families whose incomes do not exceed 30 percent of the area median income *(very, very low-income)*.

This report also utilizes fire hazard ratings, used by both public and private sector organizations around the nation, as indicators of the capabilities of fire districts to protect their communities from wildfire. The Fire Suppression Rating Schedule is a common method used by the insurance industry in reviewing the firefighting capabilities of individual communities. The schedule measures the major elements of a community's fire suppression system and develops a numerical grading called a "Public Protection Classification." Ten percent of the overall grading is based on how well the fire department receives and dispatches fire alarms. Fifty percent of the overall grading is based on the number of engine companies and the amount of water a community needs to fight a fire. Forty percent of the grading is based on the community's water supply, which focuses on whether the community has sufficient water supply for fire suppression beyond daily maximum consumption.

This report uses data from the Washington State Independent Fire Hazard Rating Bureau to assess the relationship between fire hazard ratings, poverty, and potential wildfire risk. The Washington State Rating Bureau provides data for all of the fire protection ratings for fire districts in Washington State.

Ecological Risk/ Populated Areas at Risk from Wildfire

The research intended initially to examine ecological wildfire risk—the likelihood of fire occurring in different areas and the potential damage such a fire would pose—through spatial data that would indicate, on a national level, the relative risk status of wildlands across the country. This indicator was intended to provide information about the ecological condition of lands. When it became apparent that there was insufficient consistent and up-to-date data on the ecological conditions of lands, we focused the study on the potential risk of fire to populated areas.

This study focuses on two distinct elements of the Forest Service study and data on wildland urban interface. The first data set that we examine is the *Wildland Urban Interface* as defined above. The second set of data that we use is the *Wildland Intermix*—less densely populated areas in wildlands, which enabled the study to include significant portions of inhabited land in areas vulnerable to wildfire.

Federal Resource Allocation

Initially, this study intended to include data detailing all federal expenditures under the National Fire Plan, including grants to communities and hazardous fuel reduction projects on private and public lands and spatial information that would indicate where the activities took place. These data would provide a roadmap to track where federal funding was being spent, which would allow researchers to examine these data with the data layers indicating capacity and wildfire risk. The combination of these layers would provide information about how well the federal agencies were serving the areas most at risk from wildfire.

National Fire Plan Grants—National Fire Plan data for Region 6 are available in a multi-agency database (projects funded by BLM, Bureau of Indian Affairs, USDA Forest Service, and Fish and Wildlife Service). They include zip code and latitude/longitude information for each grant, based on the location of the grant recipient, and a designation for the type of project funded (fuels reduction, fire prevention, planning and education, small-diameter marketing and utilization). Because of the limitations of the grants data, the decision was made not to analyze the data numerically. This report does include maps that illustrate the allocation of National Fire Plan Community Assistance grants in Oregon and Washington in comparison with poverty and WUI and Inhabited Wildland areas.

Findings

When we began this study, we anticipated that findings would focus on the provision of services (or gaps in services) to at-risk communities. Actual findings are considerably different from this original intent, due largely to the limited availability of data and lack of monitoring information.

Overall, the findings indicate that using national datasets to illustrate the complex social and ecological factors influencing wildfire risk is limited by the very nature of these elements. Datasets available for social, economic and ecological factors are more refined and meaningful on smaller scales. Locally specific data and information provide a better indication of the relationship between wildfire and poverty and how well services for fire protection are being provided to at-risk communities. This is apparent in the data we reviewed, as well as from comments from public meetings held in southwest and central Oregon and through dialogue with national partners. Despite these challenges, specific research findings include:

1) a slightly higher percentage of poor households in inhabited wildland areas that are not considered part of the WUI;
2) poor households in Washington State are more likely to be in areas with low or no fire response capabilities than are non poor households;
3) federal land management agency information about grants to communities and hazardous fuels reduction projects is insufficient to allow an analysis of areas served or improved.

The following section describes these findings in more detail.

Poverty and Wildland Urban Interface and Inhabited Wildland Areas

The first set of findings is related to the incidence of poverty in the wildland urban interface and other inhabited forested land areas. Initial analysis using the WUI dataset resulted in maps that showed a small portion of the total forested land area, particularly in the western United States. Further investigation indicated that the federally defined "*Wildland Urban Interface*" is based on residential density that excludes many inhabited forest areas. Expanding the analysis to include wildland intermix, the less densely populated areas that are not included in the WUI, which we refer to from here on as "*Inhabited Wildlands,*" allowed us to include significant portions of rural, inhabited land in areas vulnerable to wildfire.

Table 1 illustrates the percentage of households in Oregon, Washington, and nationally in WUI and Inhabited Wildland areas and compares non-poor, poor, and very poor households. These percentages illustrate a trend in the Northwest and nationally of a greater number of poverty areas in inhabited wildland areas than in the states or nation as a whole, or in WUI areas or non-forested areas.

Results from this analysis indicate that, in general, there are more households in poverty in inhabited wildland areas than there are in the Wildland Urban Interface or in areas outside of the vegetated wildlands in the rest of the state. The researchers held regional meetings to share preliminary findings with community organizations, agencies, and citizens in poor areas to examine data at a local level. These meetings reinforced the finding that the inhabited wildland areas that do not fall within the federal WUI definition are areas with a greater number of households in poverty.

Maps of Oregon, Washington, and the United States on the following pages illustrate the data described above and provide a visual representation of the relationship between wildfire and poverty. The maps illustrate HUD units where 20% of households or more are low-income households in Wildland Urban Interface and Inhabited Wildland areas.

The study maps of Oregon and Washington clearly indicate a tremendous amount of inhabited wildland, particularly in the western United States,

Table 1—Household Location by Poverty Level and Wildland Urban Interface Designation.

Income level	Location	Overall	Fire hazard Designation Not vegetated	WUI	Inhabited wildlands
Non Poor	National	77%	79%	81%	76%
	Oregon	79%	78%	83%	77%
	Washington	79%	79%	83%	78%
Poor	National	23%	21%	**19%**	**24%**
	Oregon	21%	21%	**17%**	**23%**
	Washington	21%	21%	**17%**	**22%**
Very Poor	National	12%	10%	**9%**	**12%**
	Oregon	10%	10%	**8%**	**11%**
	Washington	11%	10%	**8%**	**11%**

that is not considered part of the WUI under the Federal Register definition (figures 1, 2, and 3). There is a relatively high level of poverty in the non-WUI rural areas (areas where the housing density is too low to be included in the WUI).

The maps of Oregon and Washington illustrate a strong relationship between poor areas and the communities in the Inhabited Wildland areas. The national numbers support this relationship as well. However, more detail is evident from the national map, which illustrates that, although there may be more poverty in the inhabited wildlands in some regions, such as the western United States, other regions may have more households in poverty in the WUI, as appears to be the case in the Southeast.

If agencies are following the Federal Register definition, the strategy to prioritize WUI lands for hazardous fuels reduction work and the funding reserved for those areas means that fewer resources are being allocated in some regions to the poorest citizens in communities that may need the most assistance.

Poverty and Protection Capability

This study provides data about the level of fire district capabilities, which is only one indicator of the capacity of a community to reduce wildfire risk. This information is provided for the state of Washington.

Table 2 illustrates the percentage of poor and non-poor households in each of four fire response categories in Washington. A small area in the west-central portion of the state did not fall under a particular response category but showed that 33.1% of households are poor. Although there are low-income populations with all levels of fire protection, the map illustrates the visual relationship between the Wildland Urban Interface and Inhabited Wildland areas, as well as poverty and protection capability. In general, a higher percentage of poor households live in areas with no or low fire response capability than do non-poor households.

Figure 4 illustrates the level of fire protection capability in relation to the Wildland Urban Interface and poverty data in the state of Washington. The map shows a relationship between high poverty areas that overlap with areas with limited to no protection capability.

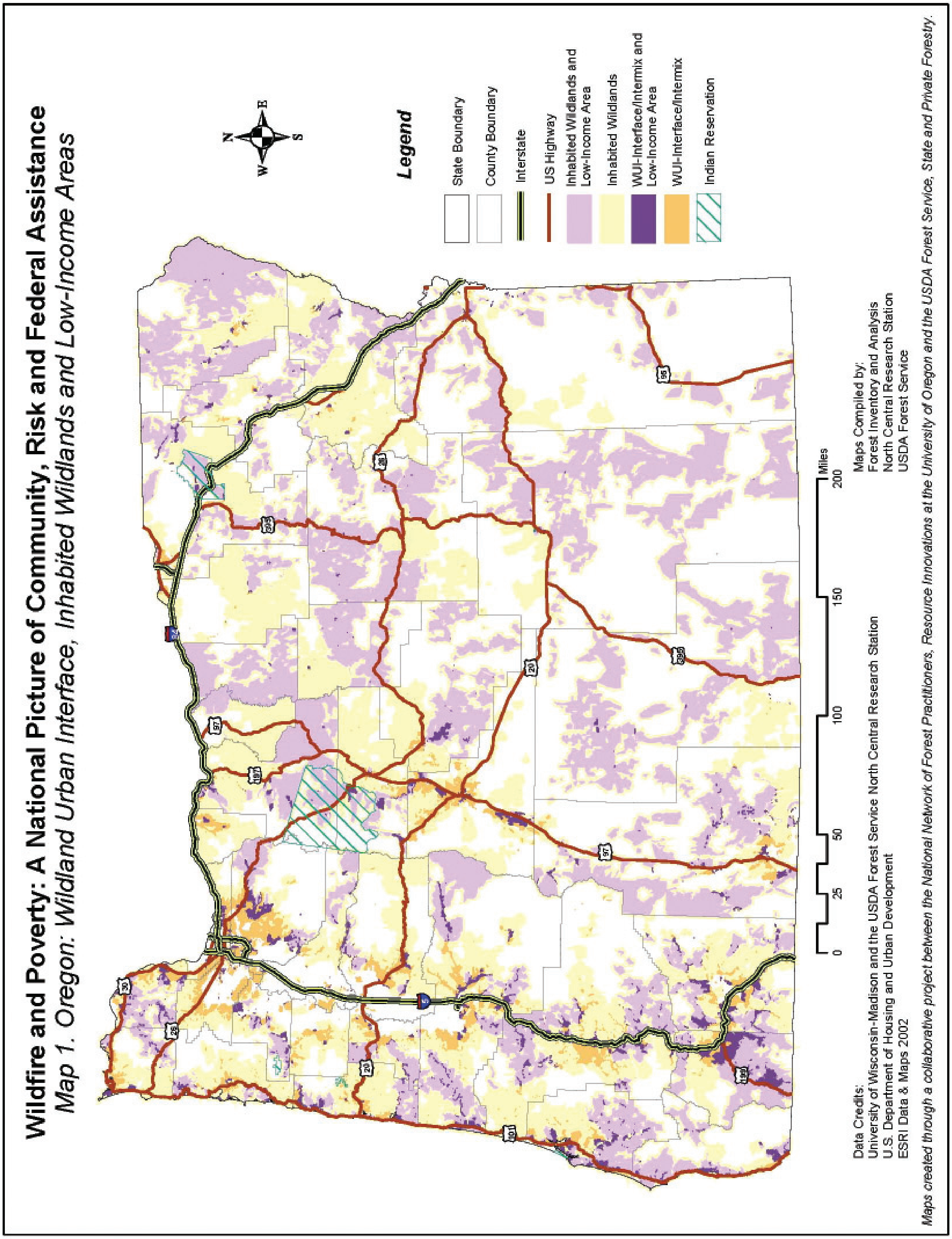

Figure 1—Oregon: Wildland Urban Interface, Inhabited Wildlands, and Low-Income Areas.

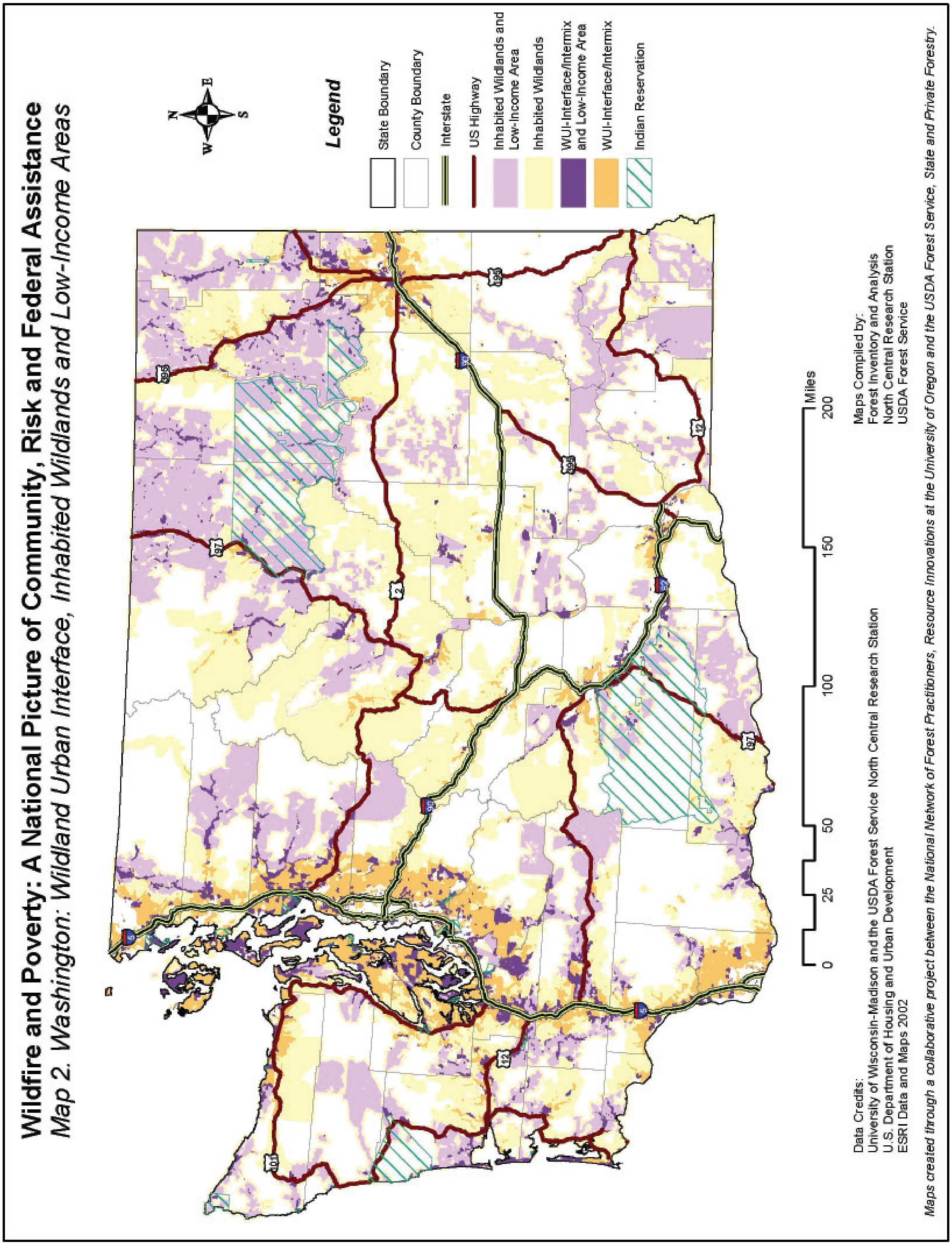

Figure 2—Washington: WUI, Inhabited Wildlands, and Low-Income Areas.

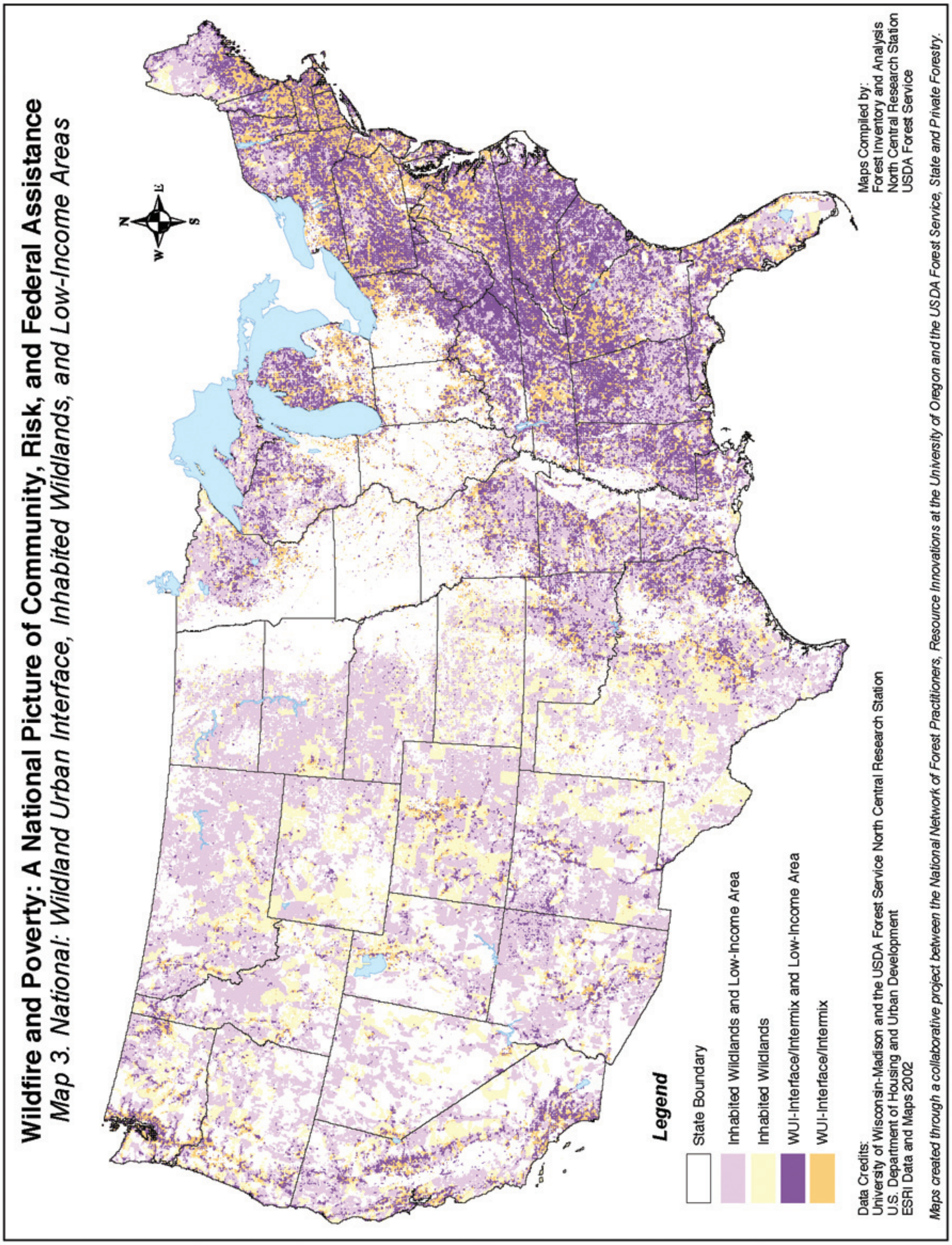

Figure 3—National: WUI, Inhabited Wildlands, and Low-Income Areas.

Table 2—Washington Households, Poverty Level and Fire Protection Capability.

Income Level	High Fire Response	Medium Fire Response	Low Fire Response	No Fire Response
Non-Poor	82%	85%	79%	77%
Poor	18%	16%	**21%**	**23%**
Very Poor	8%	7%	**10%**	**12%**

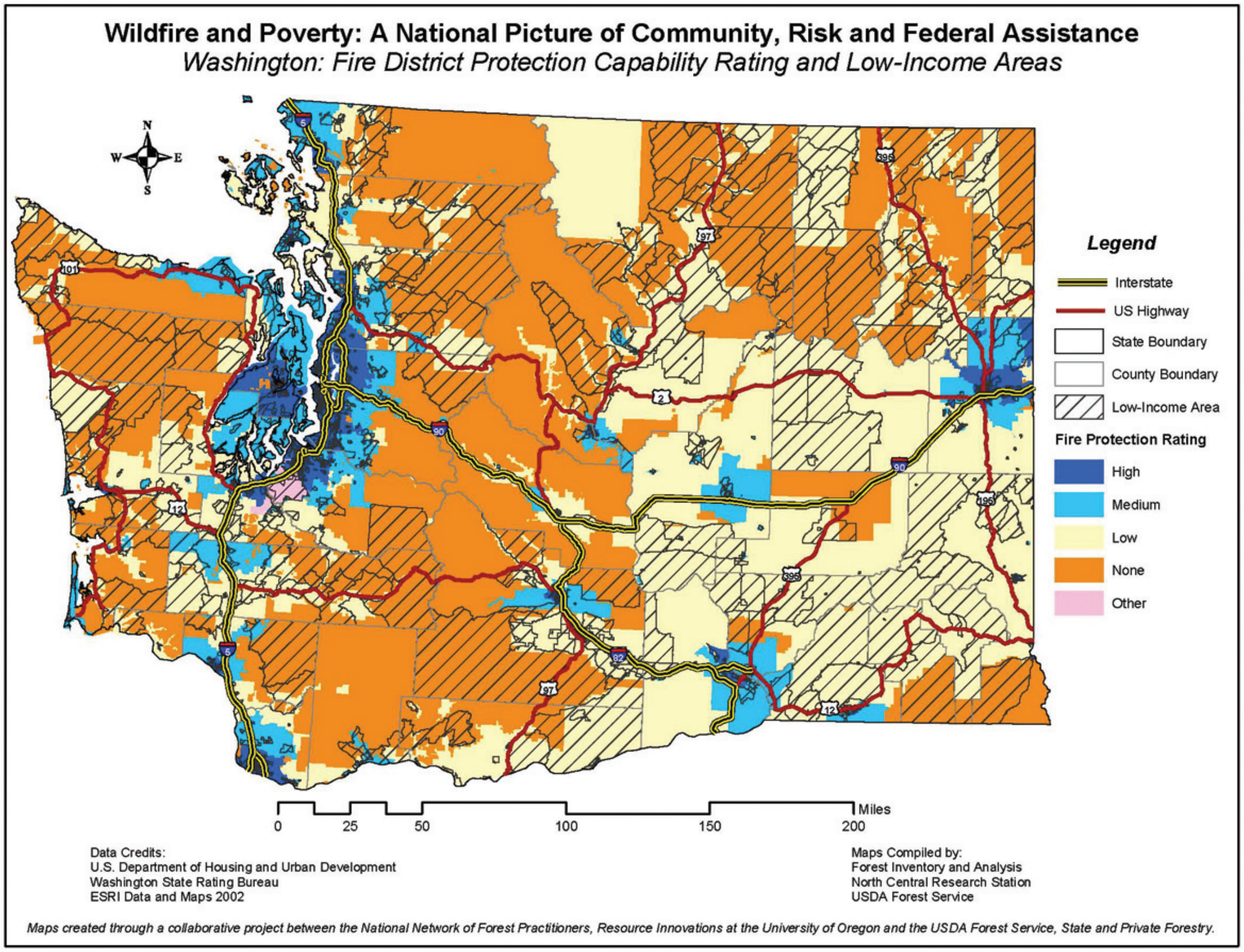

Figure 4—Washington: Fire District Rating and Low-Income Areas.

Federal Resource Allocation and Grants

The original goal of this study was to examine the provision of fire-related services and resources to low-income, low capacity communities in high-risk wildfire areas. Because of limited data about actual grant and resource allocation, it is not possible to draw reliable conclusions about resource allocation in and around poor communities. Consequently, our findings are limited to the discovery that there is inadequate monitoring of NFP expenditures and program implementation at the national level to ensure the accountability of federal programs to the goals and priorities set forth in the National Fire Plan, Healthy Forest Restoration Act, and related wildfire programs.

National Fire Plan Grants—Data about fire and aviation community assistance grants obtained through the National Fire Plan office in Region 6 (Oregon and Washington), produced maps that reflect areas that have received grants that relate to the poverty data in WUI and Inhabited Wildland areas.

The limitations of these data, as described in the research methods section, above, restricted our ability to provide percentages of poor communities that have received (or benefited from) National Fire Plan grants. The points on the map illustrate where grant funds have been received, not where grants were actually expended. In some cases, grants may have been received by agencies and organizations in county seats or municipalities that have higher income levels than the more rural areas where the funds were expended. The point data also lack information on the type and amount of treatment that occurred and the extent to which fire and fuel conditions, and community capacity have changed in low-income areas.

Recommendations

Due to the limited availability of data and the limitations of the existing data, we have focused our recommendations on improving federal agency understanding and use of social and economic factors through national inventory and monitoring efforts, and on increasing and improving assistance for low-income and low capacity communities. A summary of recommendations is provided below.

1. Redefine the areas prioritized for federal assistance to include rural areas with lower residential density (e.g., inhabited wildlands).
2. Improve systems for monitoring and evaluating the National Fire Plan and other federal fire-related program implementation by including social and economic, as well as ecological, information.
3. Immediately develop nationally consistent standards for monitoring National Fire Plan expenditures that will enable assessment of outcomes over time.
4. Develop a method for measuring community capacity in the context of wildfire.
5. Provide clear direction to federal and state land management agencies for determining “at risk” communities, giving significant consideration to social and economic factors. Target assistance and federal programs based on community needs.
6. Integrate indicators of community capacity into state, regional, and local planning and risk assessment.

7. Increase federal support and funding to programs that target assistance to "at risk" communities.
8. Conduct case studies in high wildfire risk areas to gain more in-depth knowledge about the relationship between wildfire, poverty and community capacity.

Acknowledgments

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